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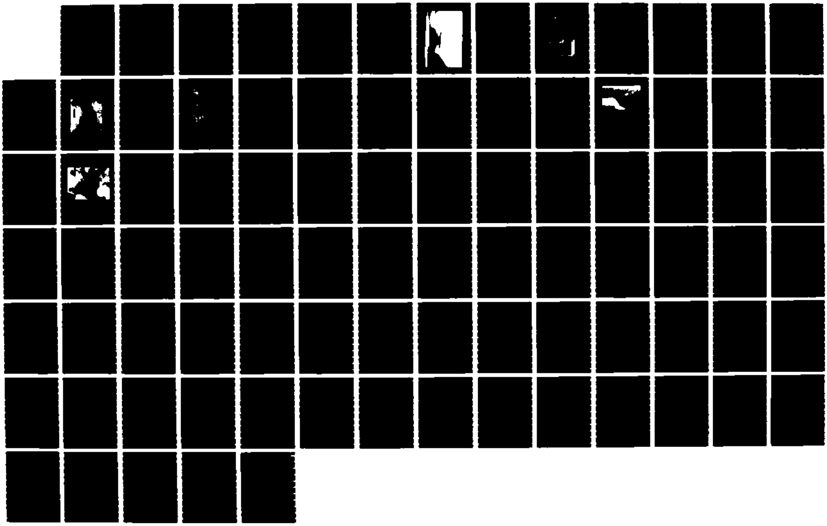

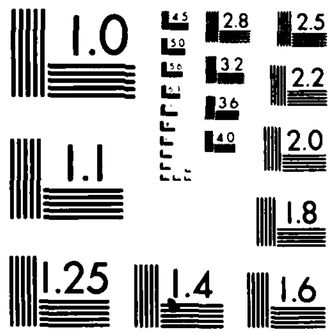
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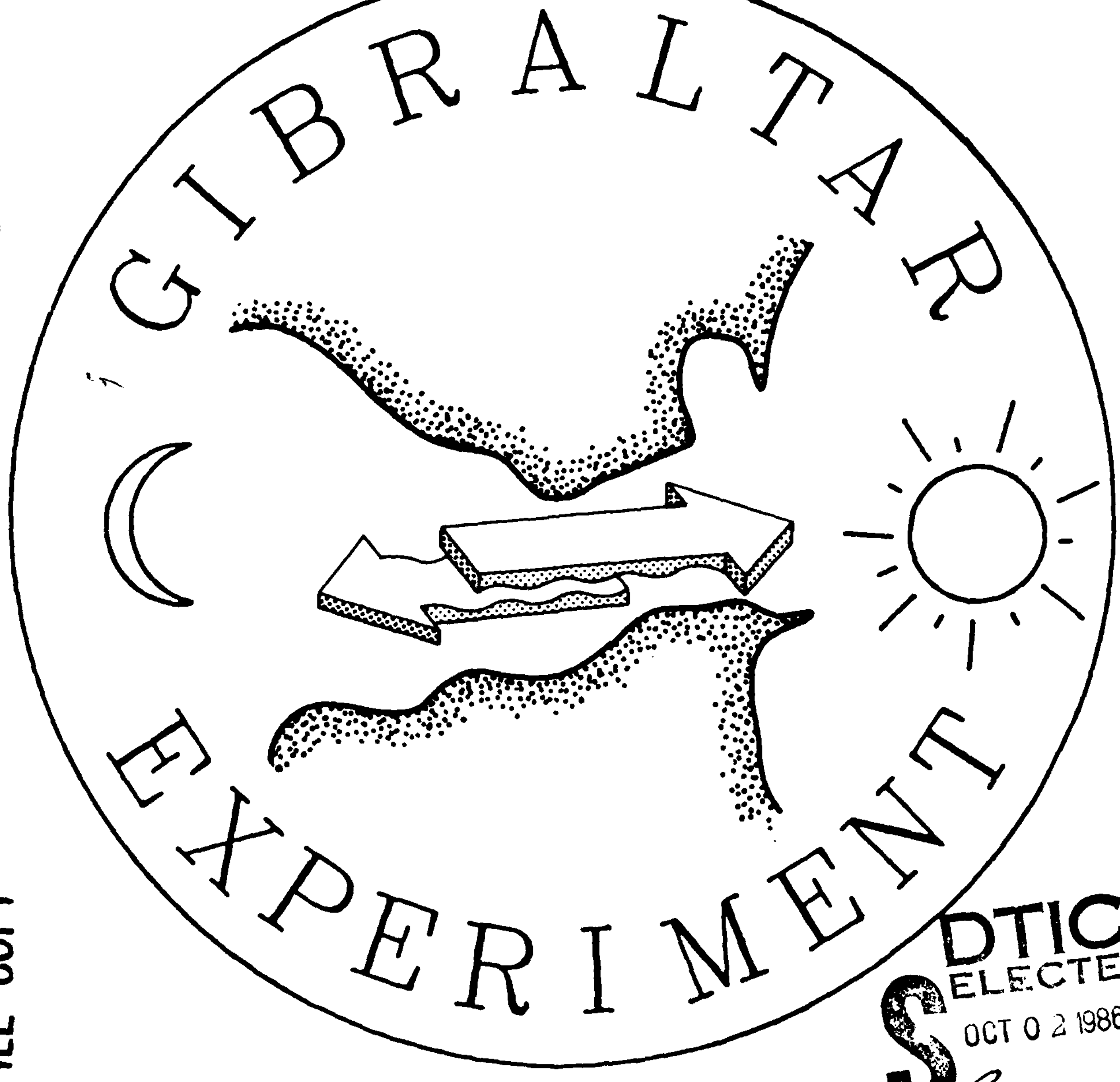

A Plan for Dynamic and Kinematic Investigations of
Strait Mixing, Exchange and Turbulence

August 1986

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GIBRALTAR EXPERIMENT

A Plan for Dynamic and Kinematic Investigations of Strait Mixing, Exchange and Turbulence

by

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Technical Report

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ABSTRACT

The flow through the Strait of Gibraltar has always held a special fascination for oceanographers. Attempts to understand and measure the strong currents in the Strait stimulated many of the early advances in oceanography (Deacon, 1971). Over the centuries, the focus of scientific investigations has shifted from understanding how the mass budget of the Mediterranean is maintained in the presence of the strong inflow of Atlantic water through the Strait of Gibraltar, to observing the outflow of Mediterranean water over the Gibraltar sill, to measuring the two-layer exchange of Atlantic inflow and Mediterranean outflow through the Strait. In the past few years the focus has again shifted to the study of how the dynamical constraints for flow through a narrow and shallow strait act to control the amount of exchange between the Atlantic and Mediterranean basins. To investigate the dynamics of flow through a strait, a year-long field experiment has been designed to measure the flows through the Strait of Gibraltar, including their time variability over tidal to seasonal time scales, and to assess the importance of friction, mixing, rotation, and nonlinear processes in controlling the exchange through the Strait. This field program, called the Gibraltar Experiment, will be carried out by a group of American, Spanish, Moroccan, Canadian and French scientists during the period from Fall 1985 to Fall 1986.

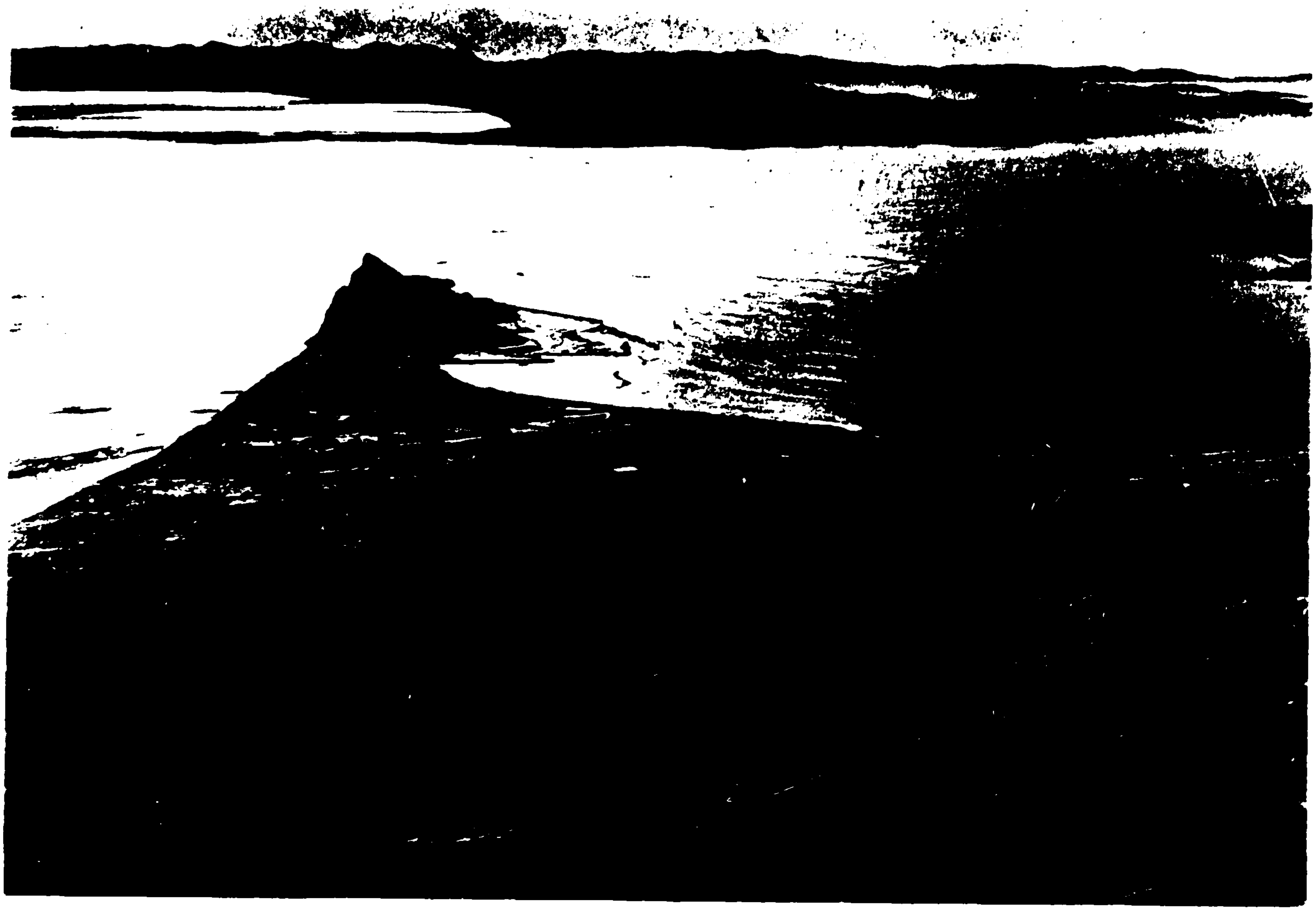

Figure 1. Aerial view of the Strait of Gibraltar taken from the Spanish side. The Rock of Gibraltar is evident in the foreground, the narrow Strait in the middle and Ceuta barely visible across the Strait.

BACKGROUND

According to legend (Bulfinch, 1979), Hercules opened the Strait of Gibraltar when he tore up the land at the end of the Mediterranean to make the Pillars of Hercules during his 10th labor (Figure 1). The strong inflow of water from the Atlantic to the Mediterranean through the Strait was known to the Greek philosophers who recognized that the inflow was much larger than could possibly be balanced by the evaporation over the Mediterranean, especially since many rivers flow into the Mediterranean and the surface flow through the Bosporus from the Black Sea also enters the Mediterranean (Deacon, 1971). Since there was no observable rise in sea level with time, how could the water balance for the Mediterranean Sea be maintained in the presence of such a strong inflow?

Studying the flow of Black Sea water through the Bosporus, Marsigli (1681) carried out an ingenious laboratory experiment in which he separated waters of different density by a barrier in a box. When he opened holes at the top and bottom of the barrier, the less dense water flowed through the surface hole while a compensating dense water current flowed through the bottom hole. He then made measurements in the Bosporus with a drogued line to demonstrate that the angle of the line indicated a deep counterflow from the Mediterranean to the Black Sea (Figure 2). The implications for the Strait of Gibraltar were clear: the surface inflow of Atlantic water must be compensated by a deep outflow of more dense Mediterranean water. Could such a deep outflow be observed in the Strait of Gibraltar?

It took 200 years before Carpenter and Jeffries (1870) observed the deep outflow by droguing a small rowboat at the eastern entrance of the

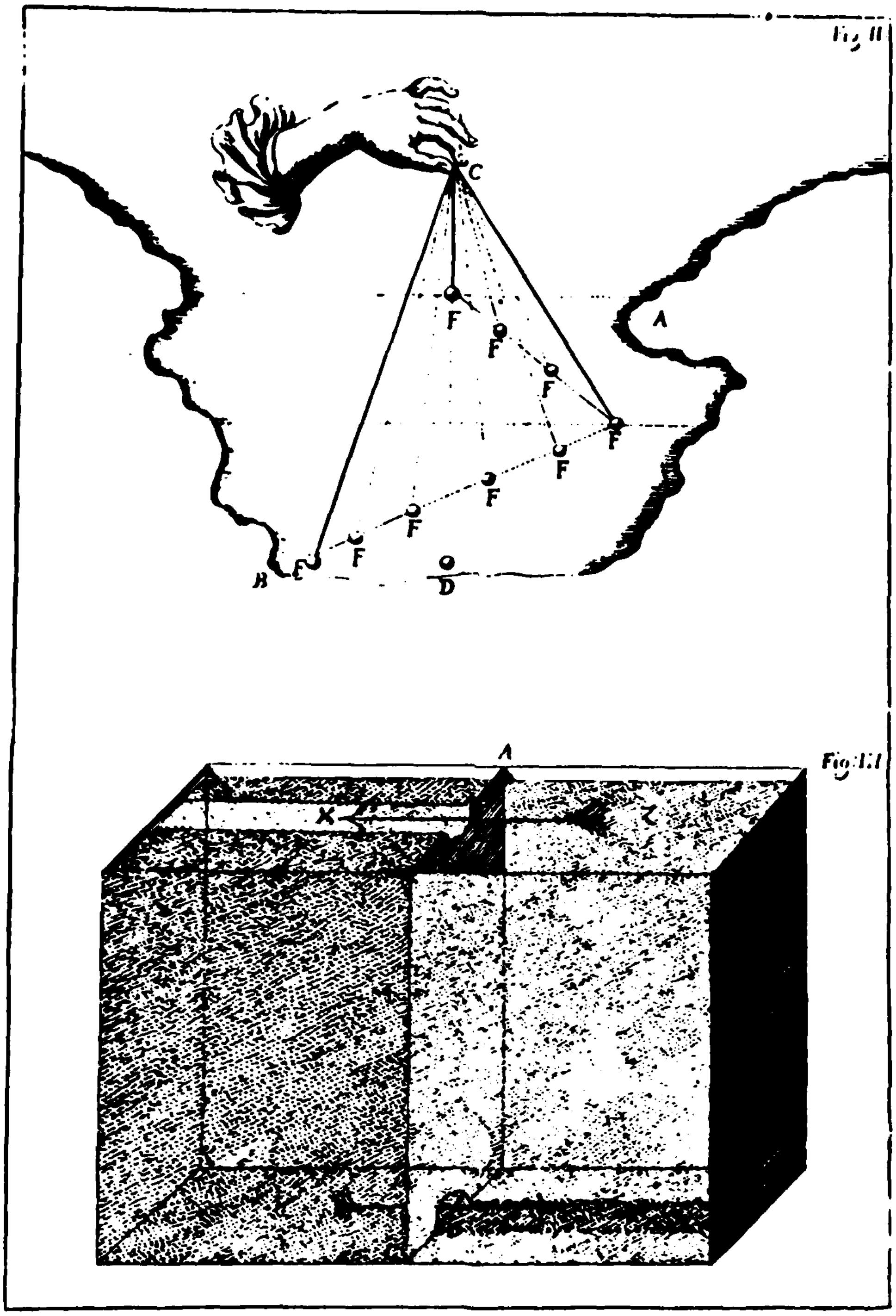

Figure 2. Marsigli's (1681) laboratory experiment to demonstrate a surface inflow and deep water outflow through a strait connecting two basins of different density and his technique for observing the deep outflow with a drogued line.

Strait. When the drogue was set at 350 m depth, the rowboat moved westward out of the Mediterranean against both the wind and the surface current. With the deep outflow finally confirmed, the focus of scientific effort changed to that of determining the magnitude of the exchange through the Strait of Gibraltar.

Nielsen (1912) was the first to use the now classic method for determining the inflow and outflow through the Strait of Gibraltar. In this method, mass and salt conservation statements for the Mediterranean basin,

$$Q_A + Q_S = E \tag{1}$$

$$Q_A S_A + Q_M S_M = 0 \tag{2}$$

are combined with estimates of the net evaporation, E, over the Mediterranean and with observations of the salinity of Atlantic water, S_A, and of Mediterranean water, S_M, in the Strait to determine the flux of Atlantic water, Q_A, and of Mediterranean water, Q_M, through the Strait:

$$\begin{aligned} Q_A &= \frac{S_M}{S_M - S_A} E \\ Q_M &= -\frac{S_A}{S_M - S_A} E. \end{aligned} \tag{3}$$

From his measurements of salinity in the Strait and estimates of net evaporation over the Mediterranean basin, Nielsen determined an inflow of 1.88×10^6 m^3 s^{-1} and an outflow of 1.78×10^6 m^3 s^{-1} through the Strait. Schott (1915) was the first to use estimates of currents to calculate directly the amount of inflow which he found to be 1.75×10^6 m^3 s^{-1}.

In the last 50 years, efforts have been made to refine the classic determinations by making more representative salinity measurements in the Strait and better estimates of net evaporation and to make more detailed direct measurements of the inflow and outflow. Determinations of the inflow and outflow, however, vary only from 0.9 to $1.9 \times 10^6\ m^3\ s^{-1}$ (Hopkins, 1978; Lacombe and Richez, 1982; Bryden and Stommel, 1982) and the most comprehensive set of direct current measurements exhibit variations in daily averaged inflow or outflow only from 0.45 to $1.84 \times 10^6\ m^3\ s^{-1}$ over 27 days with overall averages of about $1.2 \times 10^6\ m^3\ s^{-1}$ (Lacombe and Richez, 1982).

With such good agreement between classic determinations and direct measurements of the inflow and outflow, the natural question to ask is: why are the flows through the Strait of Gibraltar apparently limited to 1 to $2 \times 10^6\ m^3\ s^{-1}$ or, equivalently, why is the difference in salinity limited to 1.5 to 2.0 $^o/oo$? Do the dynamical constraints on flow through a strait combined with the physical configuration of the Strait of Gibraltar, in particular its width and sill depth, limit the exchange through the Strait of Gibraltar to 1 to $2 \times 10^6\ m^3\ s^{-1}$? Is the dominant constraint related to friction, mixing, rotation or nonlinear processes? Are the dominant constraints different for different time scales of variations in the flow through the Strait? Such questions constitute the focus of modern scientific investigations of the flow through the Strait of Gibraltar.

MODELS OF TWO-LAYER EXCHANGE

During the past three years, studies have been initiated to understand how the dynamics of flow through a narrow and shallow strait constrains the exchange between the two basins. Such questions are usually considered under the heading of hydraulic control problems. Most hydraulic control theory, however, deals with one layer flow over a dam where changing the flow rate results in a change in the height of water over the dam, or conversely, changing the height of the dam changes the flow rate. Two-layer exchange, like that in the Strait of Gibraltar, has not been much studied and is more subtle than one-layer flow, particularly if the density difference between the two layers is considered to be a variable.

Recently, Bryden and Stommel (1984) developed a simple model for the two-layer exchange in the Strait of Gibraltar assuming that *only* the salinity of the Atlantic water, the net evaporation over the Mediterranean basin and the physical configuration of the Strait, namely its width and sill depth, are known. In terms of the classic method for determining the inflow and outflow described above, this approach involves predicting the salinity of the Mediterranean water, or equivalently the salinity and density difference between the Atlantic and Mediterranean layers in the Strait, as well as the inflow and outflow. According to equations 3 derived from the mass and salt balance requirements, for a small enough salinity difference between Atlantic and Mediterranean waters in the Strait, $\Delta S = S_M - S_A$, the inflow and outflow can be made arbitrarily large. Intuitively, however, flows through a narrow and shallow strait must be dynamically limited from becoming too large. Bryden and Stommel showed

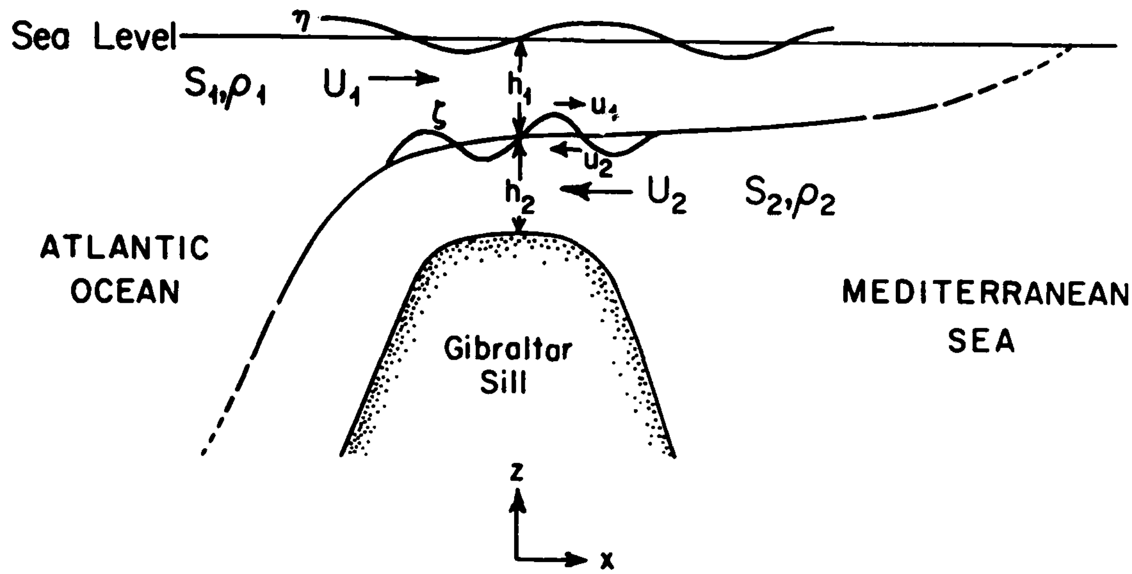

Figure 3. Schematic of hydraulic control model for the Strait of Gibraltar used by Bryden and Stommel (1984). The density difference, $\Delta\rho = \rho_2 - \rho_1$, is taken to be proportional to the salinity difference, $\Delta S = S_2 - S_1$: $\Delta\rho = \beta\ \Delta S$. The sill depth, H, equals the sum of the layer depths: $H = h_1 + h_2$; and ε is defined such that $h_1 = (1 - \varepsilon)\ H/2$ and $h_2 = (1 + \varepsilon)\ H/2$.

that the dynamics of steady, frictionless, non-rotating two-layer flow leads to a statement of hydraulic control

$$\frac{U_1^{\,2}}{(1 + \epsilon)} + \frac{U_2^{\,2}}{(1 - \epsilon)} = \frac{g\ \beta\ \Delta S\ H/2}{\rho_2} \qquad (4)$$

Kinetic Energy Potential Energy

(see Figure 3 for definitions of the symbols) which essentially requires that the kinetic energy and the potential energy associated with the exchange through the strait must be equal. Because of the mass and salt balance requirements (equations 3), kinetic energy increases as the inverse square of the salinity difference between the two layers while potential energy grows linearly with salinity difference. Thus, there is a minimum salinity difference and a corresponding maximum inflow and outflow which the dynamics of the two-layer exchange through the Strait will permit. Bryden and Stommel go on to argue that there is so much mixing in the Mediterranean that this minimum salinity difference ought to be achieved and, indeed, their estimates of minimum salinity difference, $\Delta S = 1.7\ ^{o}/oo$, and maximum inflow, $Q_A = 1.7 \times 10^6\ m^3\ s^{-1}$, and outflow, $Q_M = -1.6 \times 10^6\ m^3\ s^{-1}$, are similar to observed values in the Strait of Gibraltar. The important concept of this model, however, is that the dynamics of the two-layer flow in the Strait limits the amount of exchange between the Atlantic and Mediterranean basins.

Canizo (1984) has extended the analysis of hydraulic control in the Strait of Gibraltar to consider the effects of friction, rotation and of a triangular rather than rectangular sill section for a two-layer flow where the density difference is fixed. He concludes that friction has a

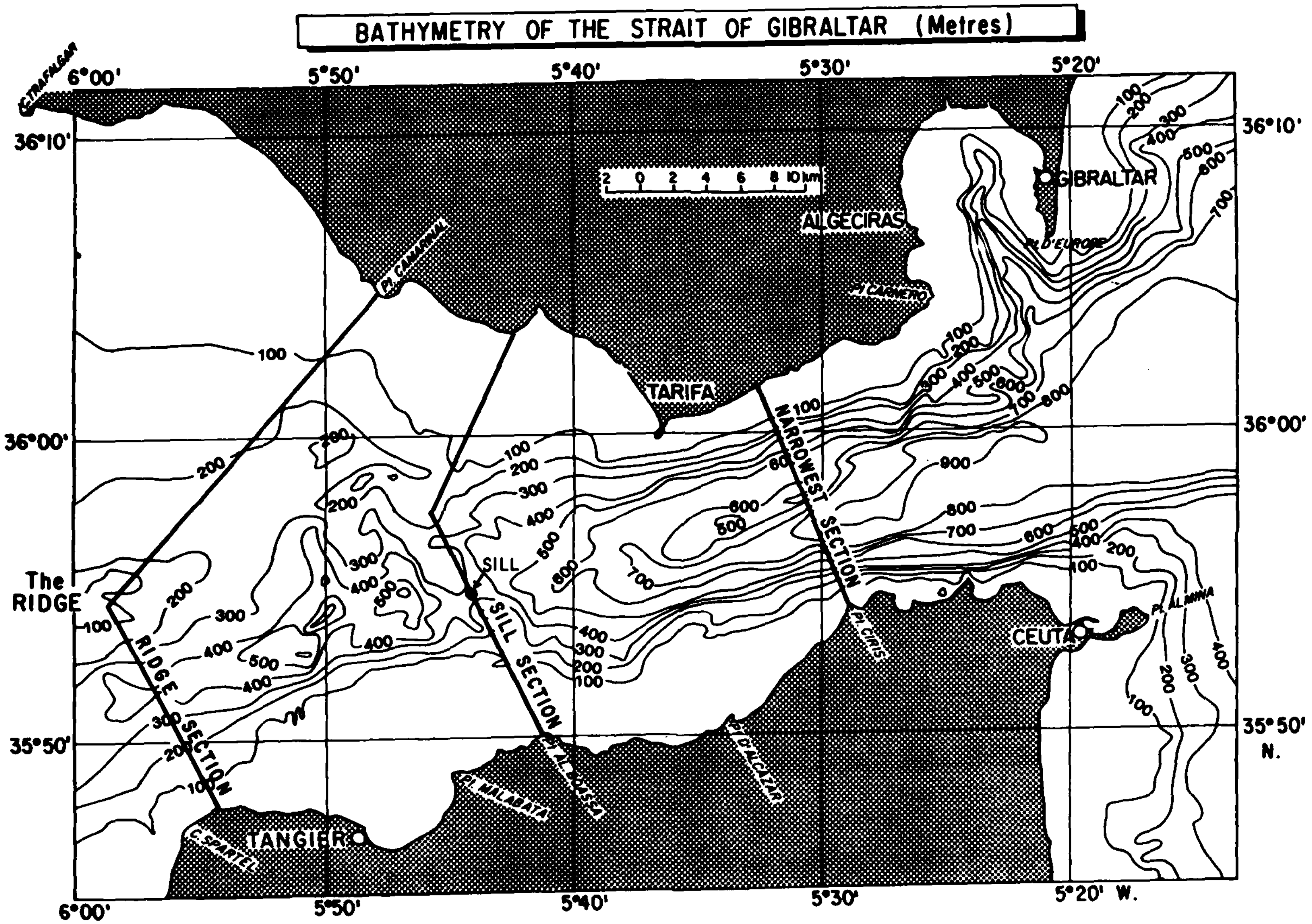

Figure 4. Three control sections which dynamically constrain the two-layer exchange through the Strait of Gibraltar according to Armi and Farmer (1985). Bathymetry in meters is from Lacombe and Richez (1982).

negligible effect on the dynamics or on the magnitude of the exchange for any reasonable value of the friction coefficient. Rotational considerations, primarily the cross-strait slope of the interface between the two layers, reduce the inflow and outflow by about 10 percent. Modeling the sill section as a triangle rather than a rectangle but with the same areas reduces the inflow and outflow by less than 5 percent.

Armi and Farmer (1985) have examined the Strait of Gibraltar measurements reported by Lacombe and Richez (1982) and conclude that there are three sections in the Strait where the composite Froude number

$$F_C = \left(\frac{U_1^2}{h_1} + \frac{U_2^2}{h_2}\right)/(g\ \Delta\rho/\rho_0)$$

achieves a critical value of 1 indicating that the flows are subject to internal hydraulic control at these sections (Figure 4). The principal hydraulic controls are exerted at the sill section, which has minimum cross-sectional area and where the flows in both layers contribute to the critical composite Froude number, and at the narrowest section just east of Tarifa where the upper Atlantic layer flow essentially achieves critical Froude number. Armi and Farmer find that the geographical displacement of the narrowest section to the east of the sill section combined with the hydraulic control criterion, which is basically an asymmetry condition for the flow, acts to reduce the exchange below that for a single control section. The section north of Cape Spartel at the western entrance to the Strait is the third control section where the lower Mediterranean layer flow achieves critical Froude number. Canizo agrees that there are multiple control sections in the Strait of Gibraltar and estimates that the

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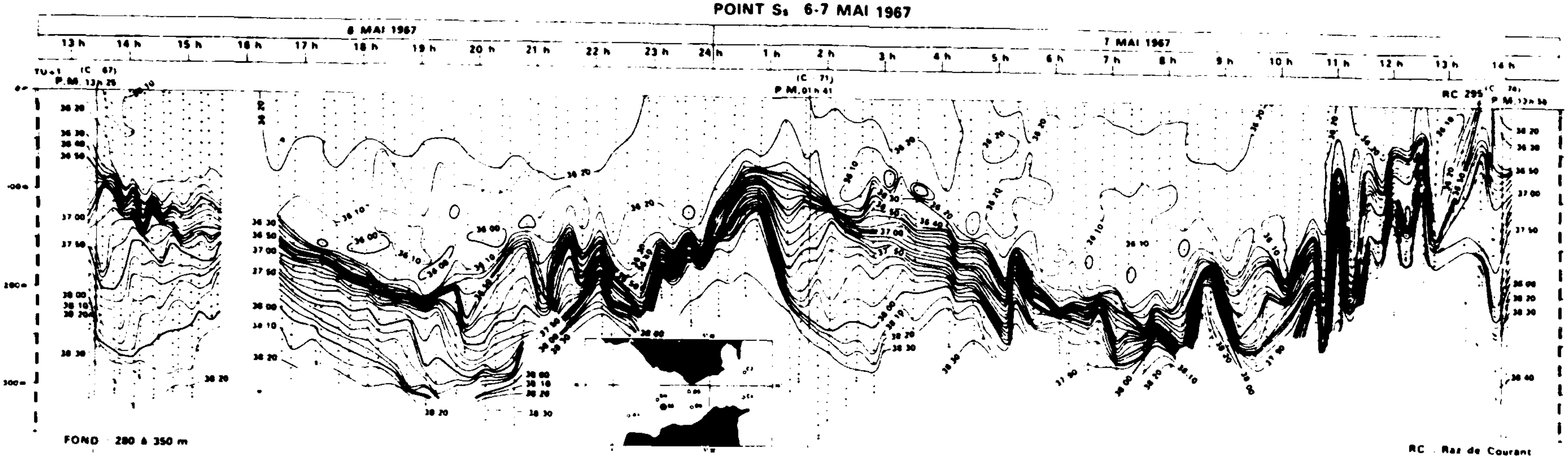


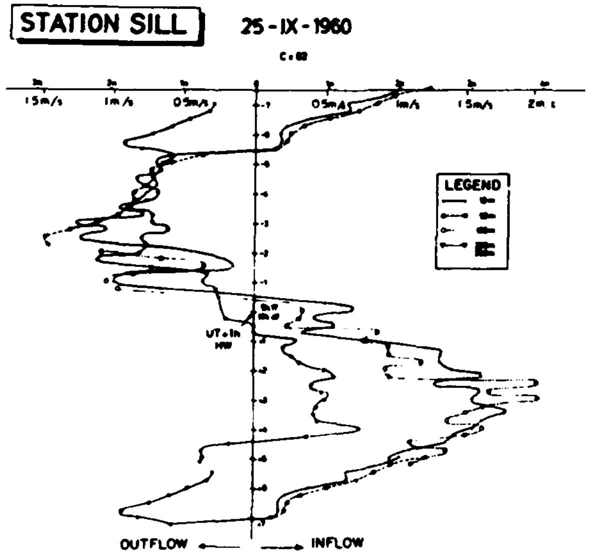


Figure 5. Temporal variation of the interface between Atlantic and Mediterranean waters and of the currents at 10, 50, 100 and 200 m depths at the sill in the Strait of Gibraltar (Lacombe and Richez, 1982 and 1984).

addition of the narrowest section to his hydraulic control analysis decreases the exchange by 30 percent from its value when only the sill section is included.

Canizo and Farmer and Armi are presently investigating the time-dependent hydraulic control problem for the Strait of Gibraltar. Given that the mean flows are hydraulically critical, what effects do time variations in the inflow and outflow and in the layer depths have on the nature of the exchange through the Strait? There are clear variations in layer depth and velocity over the tidal cycle (Figure 5); variations in wind stress and atmospheric pressure are reputed to cause variations in inflow or outflow over periods of a few days (e.g. Grundlingh, 1981 and Stanton, 1983); and the magnitude of the exchange through the Strait may vary on seasonal time scales (e.g. Parrilla and Kinder, 1985). Is the dominant dynamical constraint limiting the exchange through the Strait different for fluctuations of different time scales?

Each of these modeling studies is a particular approach to understanding how the internal dynamics of two-layer flow through a strait constrains the exchange through the Strait of Gibraltar. Even with simplifying assumptions, the theoretical problems are notoriously difficult. The complete theoretical problem including realistic width and depth variations, rotation, nonlinear processes, friction, mixing and time dependence remains "inaccessible" (Lacombe and Richez, 1982). Specific measurements, however, can help these modeling efforts both by showing which simplifying assumptions are reasonable and by isolating the dominant dynamical processes operating in the Strait of Gibraltar.

MOTIVATIONS FOR THE GIBRALTAR EXPERIMENT

There are three broad goals in carrying out a new set of comprehensive measurements in the Strait of Gibraltar. The first goal is to define the magnitude of the exchange between the Atlantic and Mediterranean basins by measuring the inflow and outflow through the Strait and their variations over tidal to seasonal time scales. The second is to assess directly the effects of rotation, friction, mixing and nonlinear processes in dynamically controlling the amount of exchange through the Strait. The third goal is to define an efficient method for long-term measurement of the flows through the Strait so that the interannual variability in the exchange between Atlantic and Mediterranean basins can be monitored.

To understand how the internal dynamics of the two-layer flow through the Strait of Gibraltar controls the amount of exchange between the Atlantic and Mediterranean basins, it is of paramount importance to measure the exchange, that is to measure both the inflow of Atlantic water and outflow of Mediterranean water through the Strait and the salinity or density difference between them. Monitoring the inflow and outflow over a complete annual period should elucidate the nature of the exchange process and how it changes for different time scales of forcing: tidal forcing at semi-diurnal, diurnal and fortnightly periods; forcing at 3 to 7-day periods due to weather-related fluctuations in wind stress and atmospheric pressure; and forcing at annual periods due to seasonal changes in net evaporation over the Mediterranean basin, in local wind stress or in water mass properties near the Strait. Comparing the variations in inflow or outflow

with variations in forcing functions should provide powerful clues as to which dynamical constraints are most effective in limiting the exchange for different time scales. To measure the inflow and outflow through the Strait and the density differences between them, direct measurements of velocity, temperature and salinity are needed throughout the water column, across at least one cross-section of the Strait, for a complete annual cycle.

In addition to monitoring the exchange, it is also necessary to study directly the dynamical processes operating in the Strait of Gibraltar. In particular, it would be helpful to assess the importance of rotational effects, friction, mixing and nonlinear processes in determining the structure and magnitude of the exchange. For each of these individual, dynamical processes, specific hypotheses to be tested with new measurements in the Strait can be described. The results of testing these hypotheses will guide future theoretical models as well as improve general dynamical understanding of two-layer flow through a narrow and shallow strait.

Traditionally, rotation is said to cause a banking of the interface between Atlantic and Mediterranean waters against the northern boundary of the Strait of Gibraltar (Sverdrup, Johnson and Fleming, 1942). For a geostrophically balanced velocity difference between the Atlantic inflow and Mediterranean outflow of 100 cm s^{-1}, the interface would be expected to slope about 40 m across a 10 km-wide Strait. Because of large tidal period variations in interface depth and the limited temporal sampling possible with hydrographic casts, such a cross-strait slope is difficult to observe in historical measurements (Gascard and Richez, 1985). With moored

time series measurements of temperature and conductivity across the Strait, averaging over the tidal oscillations should quickly reveal whether or not such an interface slope exists for time scales longer than a day.

Dynamic models of the flow through the Strait of Gibraltar sometimes assume that the potential vorticity of the outflowing or inflowing water is constant. For example, Whitehead, Leetmaa and Knox (1974) treat the outflow as having zero potential vorticity, because in its source region in the Mediterranean the lower layer is very deep. In the Strait, the lower layer has relatively small depth so its relative vorticity, $\partial u/\partial y$, must essentially equal the planetary vorticity, f: $\partial u/\partial y = f$. Thus, the westward outflow velocity must increase southward across a 10 km-wide Strait by 90 cm s^{-1}. The largest outflow then would be on the southern side of the Strait and, because the horizontal shear is so strong, there could be a reversal to eastward flow in the lower layer on the northern side. In a similar argument, the eastward inflow of Atlantic water might be expected to be strongest on the northern side of the Strait with a possible reversal to westward flow on the southern side. Time series velocity measurements across the Strait should reveal whether such strong horizontal shears exist in the inflowing and outflowing layers.

Arguing that the Rossby radius of deformation is larger than the width of the Strait, Bryden and Stommel (1984) neglected rotational effects in their analysis of the dynamical control of the exchange through the Strait of Gibraltar. The definition of the radius of deformation, however, is ambiguous for a strait with variable depth; and, because of the nonlinear nature of the hydraulic control condition (4), cross-strait variations in

layer depths or inflow and outflow velocities could fundamentally change the nature of the control criterion. Thus, a specific objective of the Gibraltar Experiment is to investigate the effect of rotation on the exchange through the Strait by determining the cross-strait slope of the interface and the cross-strait shear in inflow and outflow velocities and assessing their ramifications on the hydraulic control condition.

Friction is an intuitively appealing mechanism for limiting the flow through a strait. Defant (1961) emphasized its importance for determining the magnitude of the velocity through the Strait of Gibraltar. By modern standards, his assumed friction coefficient is very large and, as a result, recent studies of strait dynamics have gone to the other extreme and assumed frictionless dynamics. Friction must be important in reducing the velocity to zero at the bottom and, hence, in altering the hydraulic control condition for two-layer flow by reducing the lower layer transport somewhat. Direct measurements of the velocity profile near the bottom should determine the appropriate bottom friction coefficient for the Strait of Gibraltar. Friction may also be important in the interfacial region where the velocity changes from strong inflow to strong outflow over a limited depth range, especially in regions where the flows are hydraulically critical. Direct measurements of frictional dissipation in this interfacial region as well as in the Atlantic and Mediterranean layers ought to be helpful for assessing the validity of constant Bernoulli function (or constant kinetic plus potential energy) in each layer in the along-strait direction which is used in most hydraulic control models.

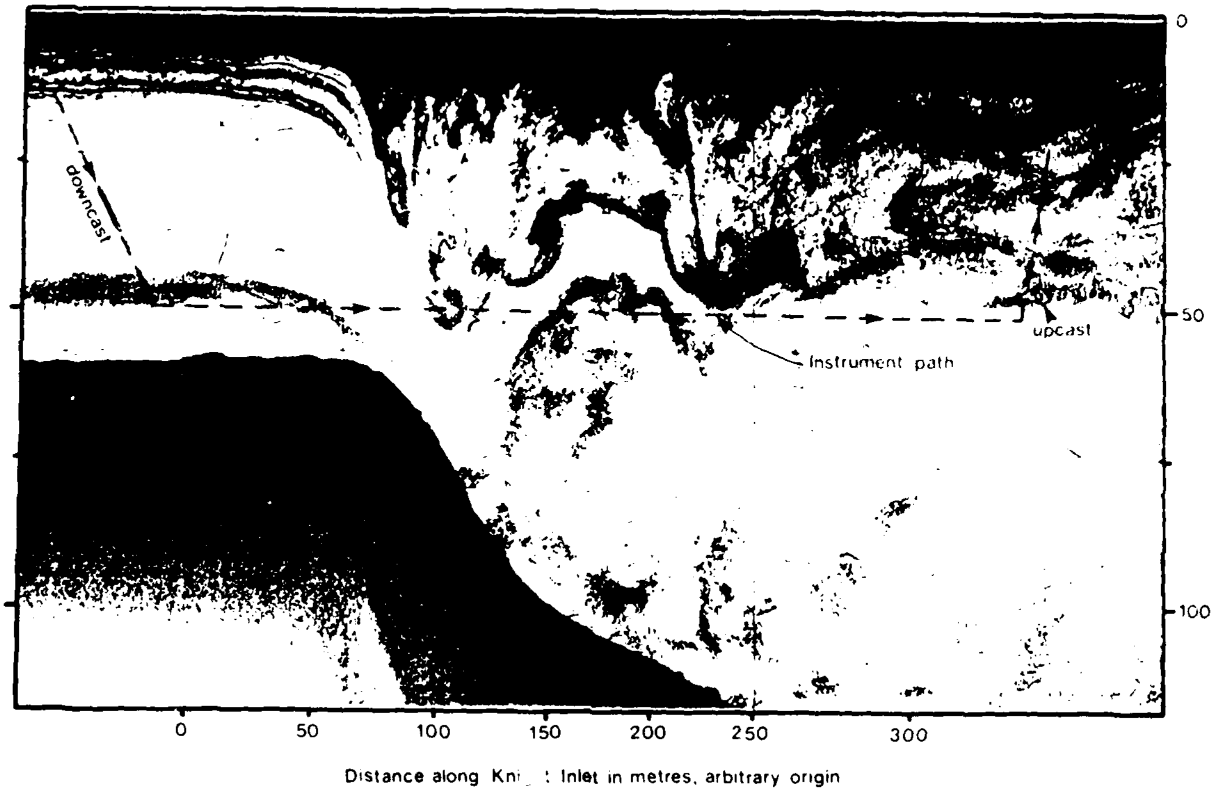
Mixing between Atlantic and Mediterranean layers is a particularly

difficult question to address theoretically. In a sense, the limiting solution obtained by Bryden and Stommel (1984) suggests that mixing must be suppressed throughout most of the Strait of Gibraltar since the Mediterranean water must arrive at the controlling sill at the western entrance to the Strait in pure form. If there were much mixing in the Strait, as implied by Sverdrup, Johnson and Fleming (1942) who chose a salinity of only 37.75 $^{0}/oo$ for the outflowing Mediterranean water, then the inflow and outflow must increase to maintain the mass and salt balances for the Mediterranean basin according to equations 3. Recent observations (Bryden and Stommel, 1982) suggest that basically pure Mediterranean water with salinity greater than 38.4 $^{0}/oo$ is present in a thick lower layer at the sill. Thus, there may indeed be relatively little mixing throughout the Strait and it may be restricted to the interfacial region. Measurements near fjord sills suggest that mixing is intense just downstream of the sill where downstream is determined from the tidal velocity (Figure 6, Farmer and Freeland, 1983). Anati, Assaf and Thompson (1977) argued that mixing occurs until the Richardson number becomes stable so that the thickness of the interface, h_I, is determined by the mixing:

$$h_I = \Delta u^2/g\Delta\rho$$

or about 50 m for a velocity difference, Δu, of 100 cm s^{-1} and density difference, $\Delta\rho$, of 2×10^{-3} gm cm^{-3} in the Strait of Gibraltar.

Like friction, mixing then acts to decrease the outflow and inflow and thus changes the hydraulic control condition from the two-layer model. Mixing also involves an energy loss from the two-layer flow. As with friction then, direct measurements of the mixing in the interfacial region and in



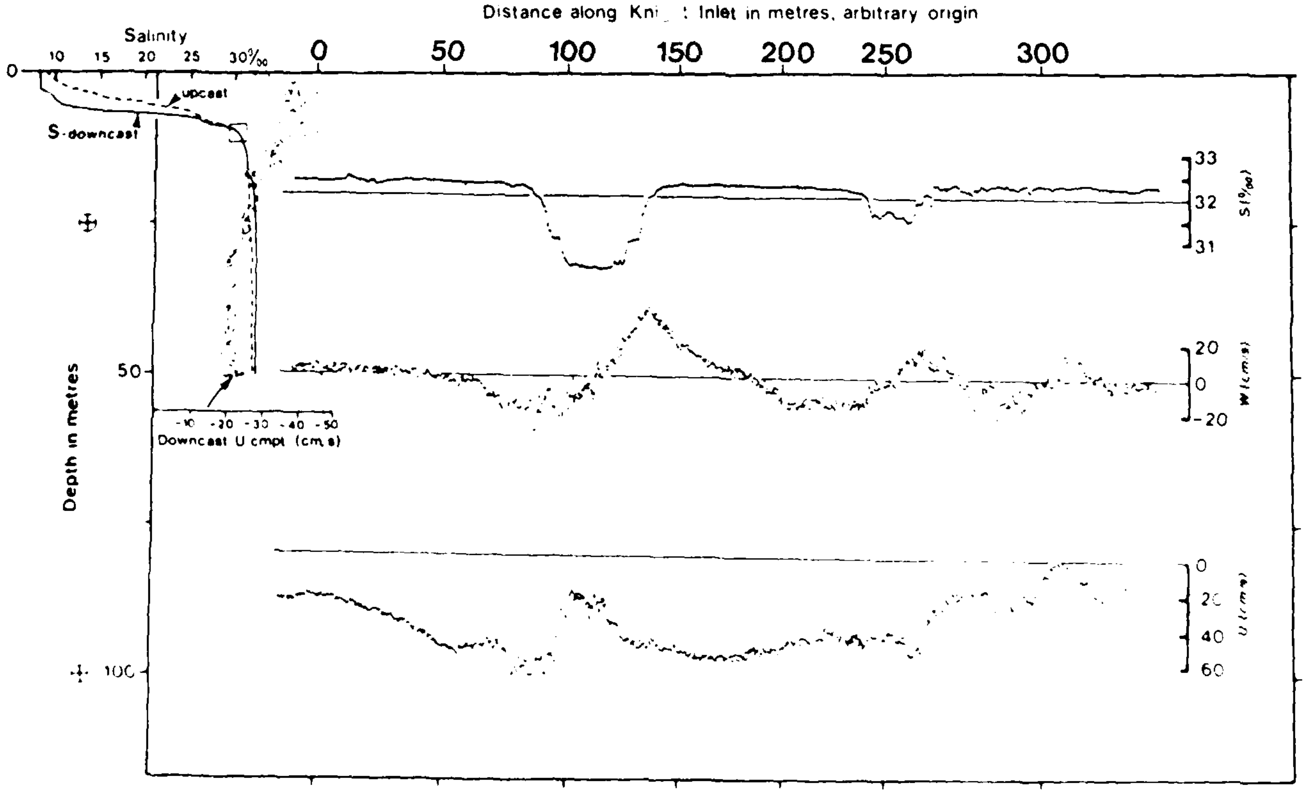


Figure 6. Acoustic profiling portrait of the flow on the seaward side of the sill of Knight Inlet along with salinity and velocity measurements obtained simultaneously from a towed instrument (Farmer and Freeland, 1983, Figure 19).

the upper and lower layers are needed to test the validity of the assumed constancy of Bernoulli function along the Strait in hydraulic control models.

Lastly, it is important to understand the role of nonlinear processes in the dynamics of the flow through the Strait of Gibraltar. Armi and Farmer (1985) estimated composite Froude numbers in various parts of the Strait to conclude that there are 3 sections of hydraulic control where U^2/h essentially equalled $g\, \Delta\rho/\rho_0$. More comprehensive measurements of velocities and laye depths are needed to determine where and when the flow achieves critical Froude number: only at the 3 control sections? only during certain parts of the tidal period? Are the control sections separated by subcritical regions where $U^2 < g\Delta\rho h/\rho_0$? Does the flow become supercritical ($U^2 > g\, \Delta\rho\, h/\rho_0$) anywhere or anytime? In addition to measuring the Froude number in various parts of the Strait, the propagation characteristics of fluctuations in the upper and lower layers can be used to define the control regions. For supercritical flow, fluctuations only propagate downstream; for subcritical flow, fluctuations may propagate upstream; and for critical flow, fluctuations are stationary. Thus, measuring the along-strait propagation of fluctuations in the upper and lower layers should help to isolate the regions of critical, supercritical and subcritical flows.

A final goal for the Gibraltar Experiment is to design an efficient measurement strategy for long-term monitoring of the inflow and outflow through the Strait of Gibraltar. It is possible that a single mooring strategically deployed on the sill section could provide long-term

measurements of the inflow and outflow. Alternatively or in addition, a set of tide gauges and a set of deep pressure gauges on the northern and southern sides of the Strait might allow accurate estimates of the inflow and outflow to be made. Comparison of the comprehensive measurements of the inflow and outflow during the Gibraltar Experiment with individual indices should allow design of an efficient strategy for long-term monitoring of the exchange between the Atlantic and Mediterranean basins. Because Mediterranean water masses have relatively short renewal time scales of 10 to 100 years, an interannual change in the properties of Mediterranean water masses exiting the Strait or in the magnitude of the flows through the Strait might be a harbinger of larger-scale climate changes. For this reason, monitoring of the flows through the Strait of Gibraltar should be an integral component of world climate research programs such as the World Ocean Circulation Experiment.

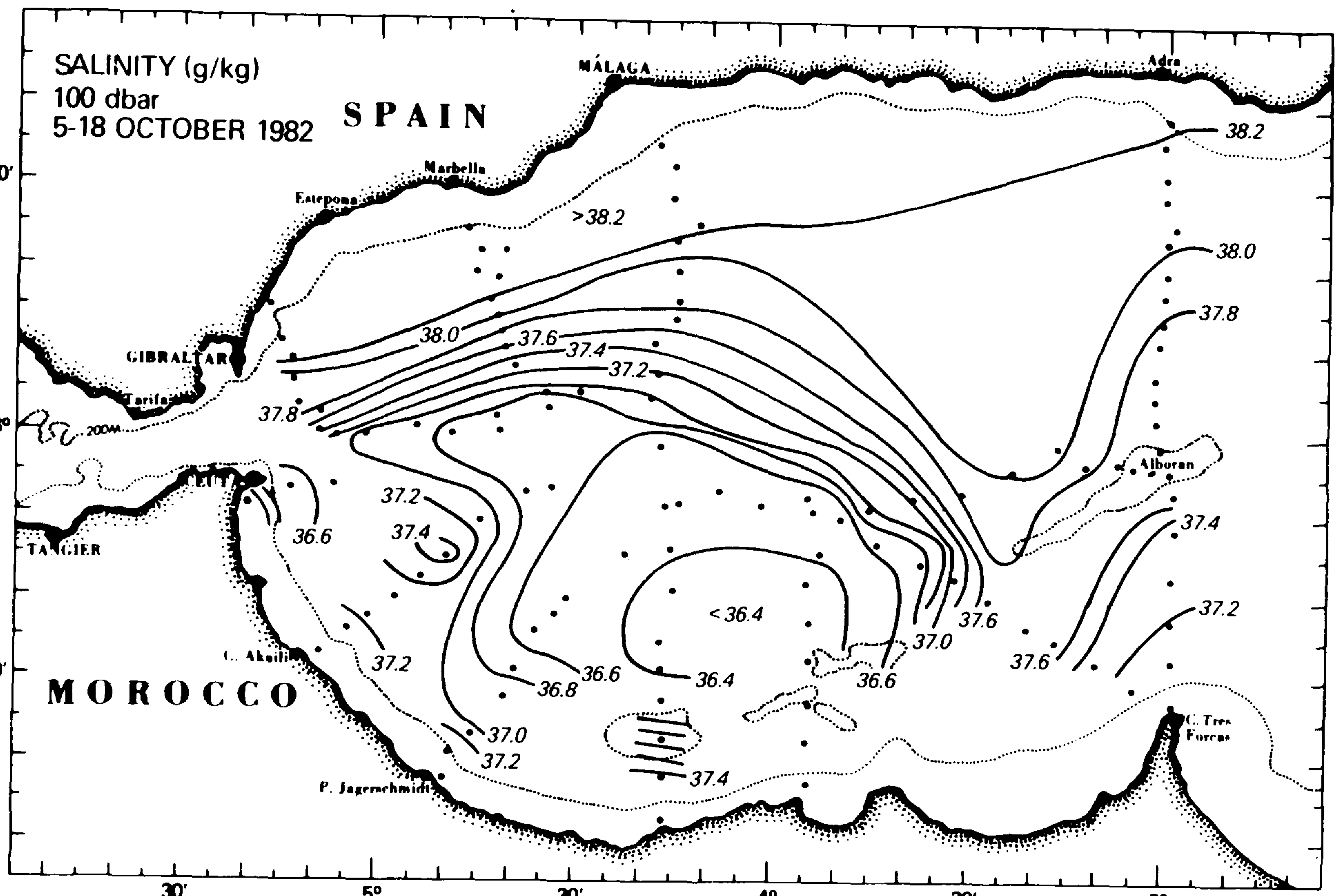


Figure 7. Salinity at 100 dbar to illustrate the anticyclonic gyre in the Alboran Sea (Dónde Va Group, 1984).

INFLUENCE OF THE FLOWS THROUGH THE STRAIT OF GIBRALTAR ON THE GENERAL CIRCULATION OF THE ATLANTIC AND MEDITERRANEAN

Both the shallow Atlantic Water that flows into the Mediterranean Sea and the deeper Mediterranean Water that flows into the North Atlantic Ocean have important influences on the oceanography of the adjacent bodies of water. Increased knowledge about the flow in the Strait provides better understanding about these larger areas of the world ocean.

The Atlantic Water enters the Alboran Sea as an energetic jet (speeds greater than 1.5 m/sec), and nearly always forms an anticyclonic gyre that extends across the entire sea (Lanoix, 1974; Donde Va Group, 1984; Parrilla and Kinder, 1985; Figure 7). Modeling studies, which have included analytical, numerical, and laboratory techniques, have shown that the Atlantic Water inflow through the Strait is the critical forcing mechanism for the gyre, and that variations in this forcing cause fluctuations in the size and strength of the gyre (Nof, 1978; Whitehead and Miller, 1979; Preller, 1985). The transport and velocity (which are not independent in most formulations), the entry angle, and the horizontal shear of the inflowing Atlantic jet all seem to influence the gyre in these studies.

The Atlantic Water continues eastward, mostly following the North African coast. In the eastern Alboran Sea, the current often forms meanders that are comparable in scale to the Alboran gyre, and farther east off the coast of Algeria, the instabilities occur as large eddies which sometimes are detached from the current (Arnone and La Violette, 1985; Millot, 1985).

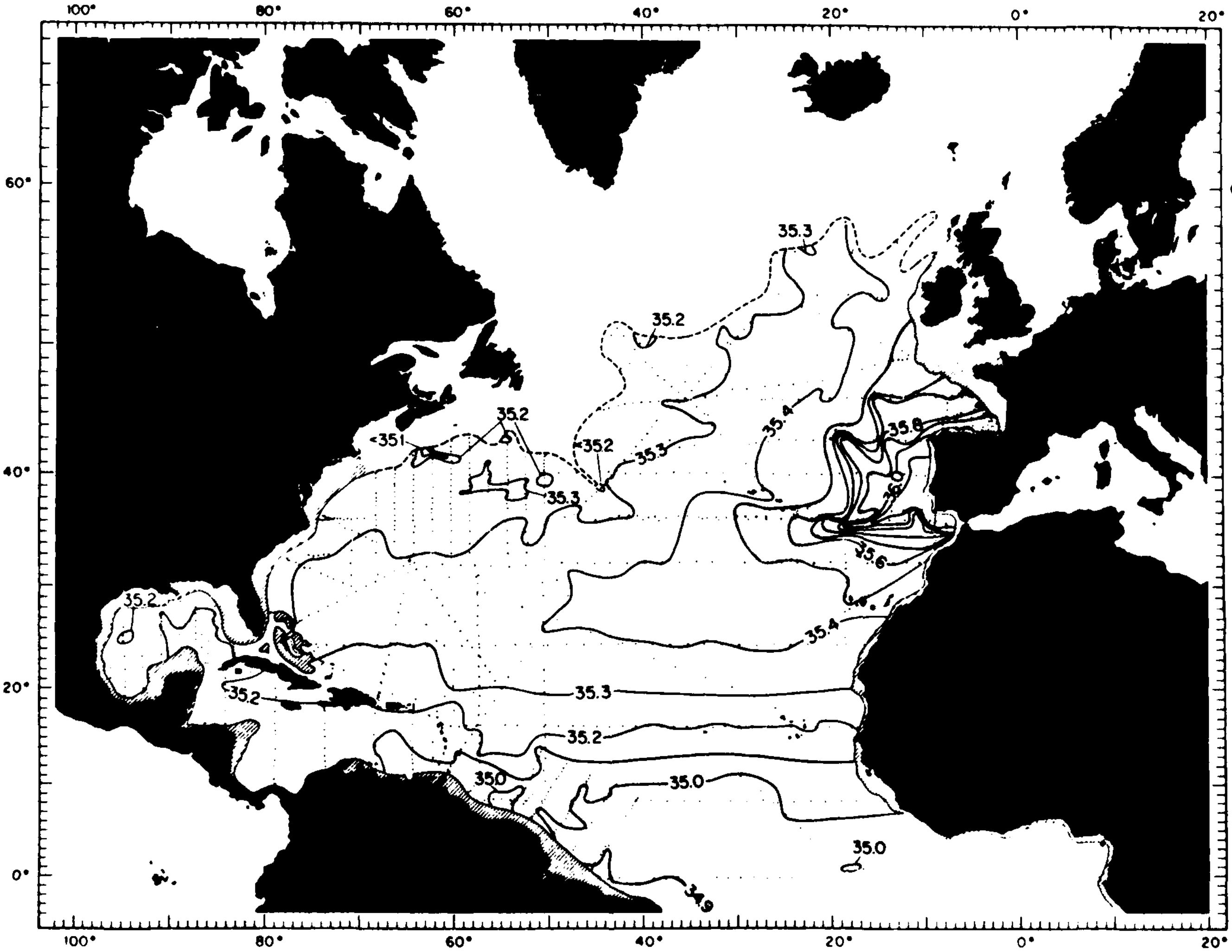


Figure 8. Salinity (‰) at the 10-°C surface to illustrate the penetration of the Mediterranean water salt tongue in the North Atlantic (Worthington, 1976).

As it exits the Strait in the Gulf of Cadiz, the Mediterranean outflow entrains ambient Atlantic Water as it follows the Iberian continental slope and sinks toward an ultimate depth near 1000 m in the North Atlantic (Ambar and Howe, 1979a, b). The outflow, perhaps bathymetrically influenced, takes multiple paths and shows considerable temporal variability (Zenk, 1975). Rotation, bottom friction, entrainment, and variability in the outflow through the Strait all seem to play a role in reducing the temperature and salinity anomaly of the outflow as it descends to its equilibrium depth (Smith, 1975).

The Mediterranean outflow exerts a profound influence well beyond the Gulf of Cadiz. Throughout mid-depths in the North Atlantic, there exists a marked salinity maximum which is directly traceable to the Mediterranean, and which has played a central role in ideas concerning the general oceanic circulation of the North Atlantic (Figure 8; Worthington, 1976). A comprehensive theory of the North Atlantic circulation, for example, should be able to simulate and explain the large scale salinity tongue that originates at the Strait. Refined estimates of the outflow transport throughout the Strait and its variation may contribute to a better understanding of the circulation of the North Atlantic Ocean.

Recently, it has become apparent that the Mediterranean salinity anomaly may not diffuse across the North Atlantic smoothly as a broad, large-scale tongue as suggested by Figure 8. Rather, a significant part of the high salinity water may be advected discretely by large lenses embedded in the pycnocline that carry water with elevated salinities as far as the Bahamas before breaking apart (McDowell and Rossby, 1978; Armi and Zenk,

1984). The mechanism and site of the formation of these eddies is unknown, but they seem to occur frequently enough to be fundamentally important in the formation and maintenance of the high salinity plume of the Mediterranean Water in the North Atlantic. Such eddies may be formed during bursts of anomalously high outflow of Mediterranean Water exiting the Strait of Gibraltar.

DESCRIPTION OF THE EXPERIMENT

To measure the inflow and outflow through the Strait of Gibraltar and to investigate the dynamical processes controlling the exchange between the Atlantic and Mediterranean basins, a year-long experiment will be carried out in the Strait of Gibraltar from Fall 1985 to Fall 1986. The measurements are most conveniently divided into moored time series measurements and shipboard and aircraft synoptic measurements. The instruments making time series measurements include sea level gauges, bottom pressure gauges, meteorological stations, bottom-mounted profiling current meters, moored current meters with temperature and conductivity sensors and moored thermistor chains. Synoptic measurements include hydrographic sampling using CTD's (Conductivity, Temperature, Depth profilers), XBT's (Expendable Bathythermographs) and XSVT's (Expendable Sound Velocity and Temperature profilers) with water samples analyzed for nutrients, freon, tritium and trace metals, microstructure profiles using AMP (Advanced Microstructure Profiler), acoustic profiling of the density and velocity fields, and current profiling using XCP's (Expendable Current Profiler) and VCTD's (Velocity, Conductivity, Temperature, Depth profiler). All the time series instruments except for the moored thermistor chains are intended to measure through a complete annual cycle from October 1985 to October 1986. Synoptic measurements are planned for October 1985, January, March-May, July and October 1986, with the most intense period being March-May 1986.

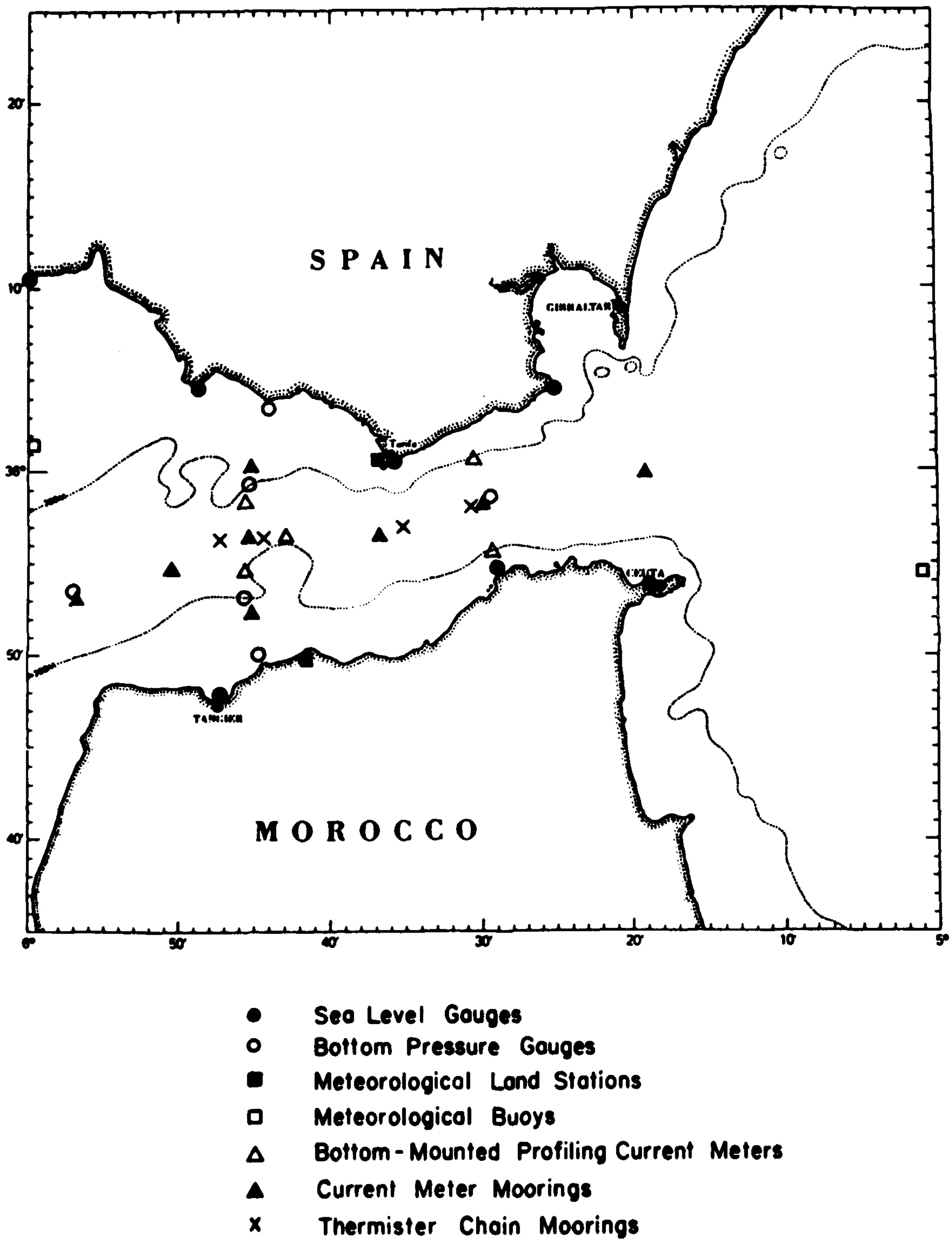


Figure 9. Moored time series measurements in the Strait of Gibraltar during the period Fall 1985 to Fall 1986.

Moored Array

Because the sill section of minimum cross-sectional area is assumed to be the region where the dynamics of the two-layer flow through the Strait primarily controls the exchange between the Atlantic and Mediterranean basins, moored instruments are concentrated on the sill section. The narrowest section just east of Tarifa, which is assumed to be a secondary control section, is also heavily instrumented. The array design and objectives of each of the types of moored instruments and the principal scientists coordinating their operations are outlined in the following paragraphs.

Sea-level gauges are to be continued by Drs. Fernandez de Castillejo and Garcia Moron at 7 locations in the Strait of Gibraltar. These gauges have been operating at 4 locations along the northern boundary of the Strait and at 3 locations along the southern boundary (Figure 9). Fluctuations in the cross-strait difference of sea level should measure changes in the surface geostrophic inflow. Fluctuations in the along-strait difference in sea level may indicate variations in the surface pressure gradient between the Atlantic and Mediterranean which can force variations in the exchange through the Strait (Bormans, Garrett and Thompson, 1984). Absolute leveling of the tide gauges, at least along the Spanish coast, is planned to determine the mean along-strait pressure gradient driving the inflow.

Bottom pressure gauges are to be deployed by Dr. Winant at 6 locations in the Strait (Figure 9). Shallow pressure gauges at 10 m depth on the northern and southern ends of the sill section will provide an additional

estimate of the cross-strait pressure gradient and hence of the surface geostrophic inflow. Pressure gauges at the 200 m-isobath on the northern and southern sides of the sill section will measure fluctuations in cross-strait pressure difference in the lower layer of Mediterranean water and provide estimates of the variations in the geostrophic outflow velocity. Deep pressure gauges deployed at the eastern and western entrances to the Strait will measure the fluctuations in along-strait pressure difference in the lower layer which can force changes in the outflow.

Meteorological stations are to be deployed by Dr. Beardsley with cooperation from Spanish and Moroccan scientists on land at Tarifa and at Punta Cires on the Moroccan coast of the Strait. In addition, surface buoys measuring atmospheric pressure and wind velocity are to be moored near the eastern and western entrances of the Strait (Figure 9) beginning in January 1986. The primary objective of these measurements is to measure the wind-stress in the Strait and the along-strait difference in atmospheric pressure which are potential mechanisms forcing fluctuations in the exchange through the Strait.

Moored current meters are to be deployed by Drs. Bryden and Pillsbury and Capt. Milleiro on 3 cross-strait moorings on the sill section (Figure 10) and 5 additional along-strait moorings (Figure 11). In order to determine salinity and density, each current meter will measure temperature and conductivity. Thus the velocity can be attributed to the Mediterranean or Atlantic layer or to the interface between them. The temperature and conductivity measurements will also monitor the depth of the interface between Atlantic and Mediterranean layers where the vertical

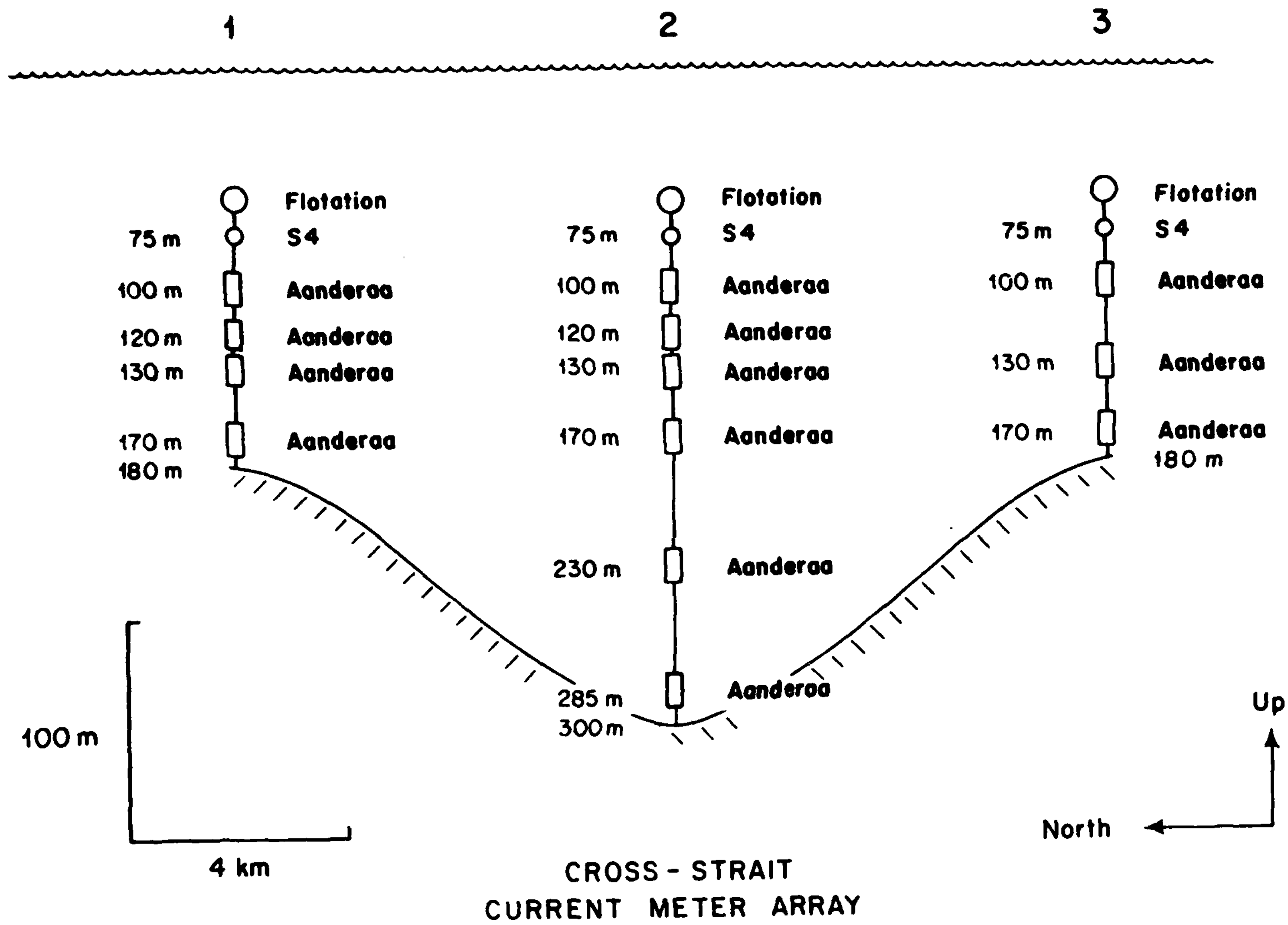


Figure 10. Moored current meters deployed across the Strait of Gibraltar on the Sill Section.

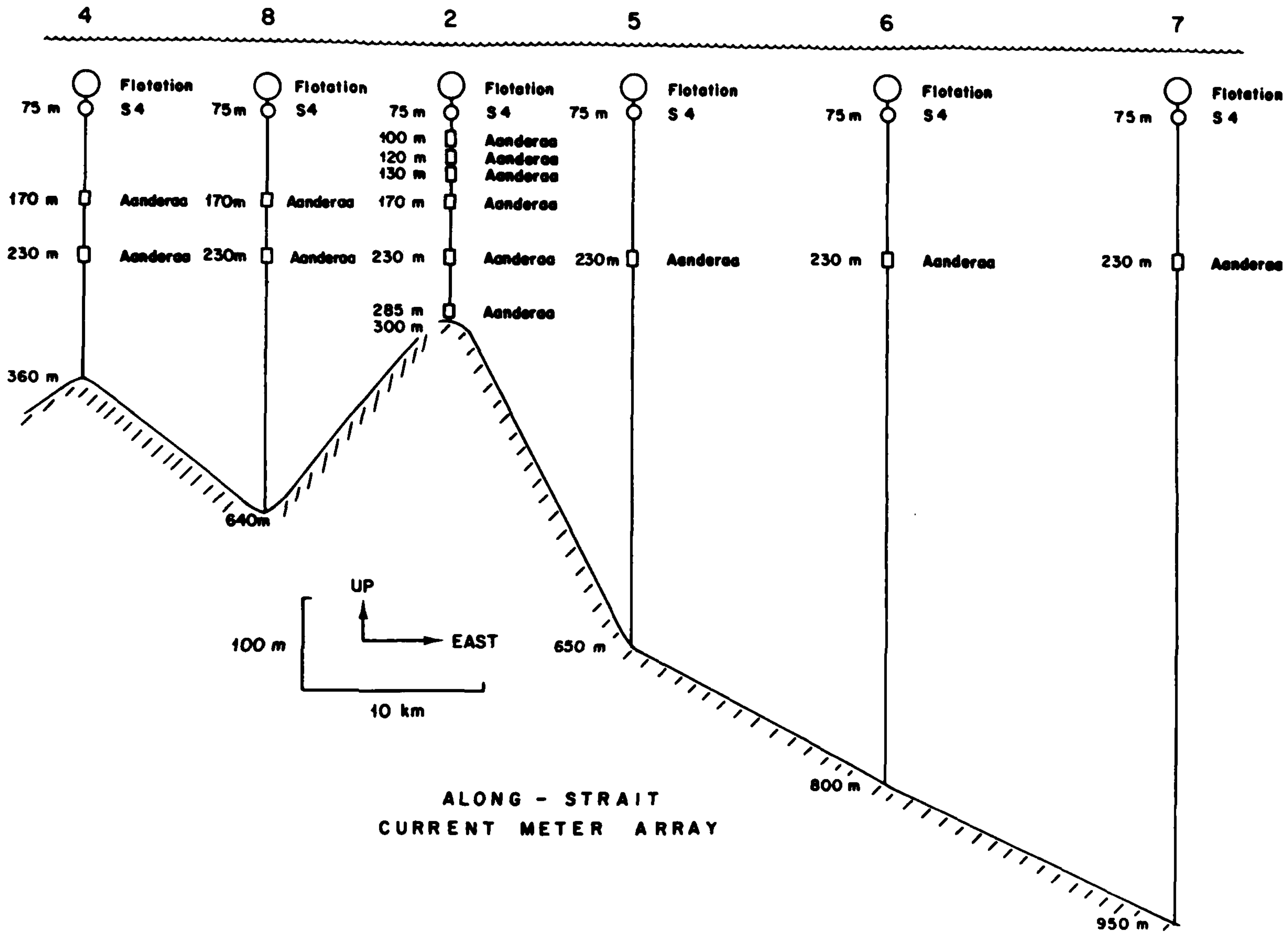


Figure 11. Moored current meters deployed along the axis of the Strait of Gibraltar.

density and salinity gradients are strongest. The cross-strait instruments are intended to measure the exchange across the sill section and determine the cross-strait structure of the interface and of the velocity in the inflowing layer at 75 and 100 m depths and in the outflowing layer at 130 and 170 m depths. The along-strait instruments are intended to provide representative measurements of inflow velocity at 75 m depth and outflow velocity at 230 m depth at 6 along-strait locations and to allow the along-strait propagation characteristics of fluctuations in both the Atlantic and Mediterranean layers to be determined as a function of frequency.

Bottom-mounted profiling current meters are to be deployed by Dr. Pettigrew at 5 locations in the Strait (Figure 9). These current meters acoustically sample the velocity at approximately 8 m-depth intervals through 300 m of the water column using the Doppler method. Because these new instruments make time series measurements of both the inflow and outflow possible for the first time, they will provide the primary measurements of the exchange through the Strait. Three instruments deployed on the sill section will measure the inflow and outflow and their temporal fluctuations. Two instruments moored on the narrowest section just east of Tarifa will help to measure the exchange and to determine if the inflowing Atlantic layer achieves critical Froude number on this second control section. Each of the bottom-mounted profiling current meters also measures bottom pressure and thus contributes to the determination of along-strait and cross-strait pressure difference fluctuations in the lower Mediterranean water layer.

Moored thermistor chains are to be deployed by Dr. Farmer during the

month-long intensive synoptic experiment in March-April 1986. The thermistor chains will measure temperature at 10 m-intervals between 100 and 200 m depth so that the fluctuations in the interface between Atlantic and Mediterranean layers can be monitored at the hydraulic control sections during the synoptic experiment.

In order to ensure the rapid sampling necessary to resolve high-frequency fluctuations, moored instruments will generally be deployed for two 6-month periods, October 1985 to March-April 1986 and March-April to October 1986. Thus, the moored instruments must be recovered and redeployed during March-April 1986. Every effort will be made to make continuous measurements of the exchange across the sill section during this turn-around phase. Thus, the bottom-mounted profiling current meters will be recovered and redeployed before the moored current meters are recovered. The moored current meters will remain out of the water during the intensive synoptic experiment when towed CTD's and AMP profilers tethered to a drifting ship might foul the current meter moorings. Because the current meter moorings provide the only measurements of interface depth, the two thermistor chain moorings are to be deployed for this month-long intensive experiment to monitor the depth of the interface as background for the synoptic measurements.

Synoptic Experiments

During the year-long period when the moored array is deployed in the Strait, there will be a series of synoptic experiments investigating the kinematics and dynamics of the flow through the Strait, of the descending outflow into the Atlantic, and of the inflow as it forms the anti-cyclonic gyre in the Alboran Sea. The measurements to be used in these experiments

and the principal scientists coordinating them are outlined in the following paragraphs.

Hydrographic measurements using CTD instruments are to be carried out 5 times by Drs. Kinder, Parrilla and Bray in October 1985, January, March-April, July and October 1986 in order to determine the seasonal variation in temperature and salinity properties of the inflowing Atlantic water and outflowing Mediterranean water. On each cruise, CTD sections are to be made along the axis of the Strait at the beginning and end of each survey and across the Strait on 5 sections including all of the suggested control sections; and 24-hour time series stations are to be taken near the sill and repeated sections across the narrowest section east of Tarifa will be made as time permits (Figure 12). On several of the cruises, the surveys will be extended into the Alboran Sea and Gulf of Cadiz to describe the near-field origin and fate of Atlantic and Mediterranean waters which flow through the Strait. Water samples on two of these extended surveys will be analyzed for nutrient concentrations by Drs. Cabanas and Minas in order to discriminate between various sources of the Atlantic and Mediterranean waters. Freon concentrations measured by Dr. Edmond and tritium and helium concentrations by Dr. Roether should help to determine the age of the Levantine intermediate water and western Mediterranean deep water exiting the Strait. Analysis for trace metal concentrations by Dr. Boyle should help determine the origin of excess heavy metals recently observed in the inflowing Atlantic water. CTD stations on each cruise near current meter and thermistor chain moorings and over bottom pressure gauges and bottom-mounted profiling current meters will help to calibrate the

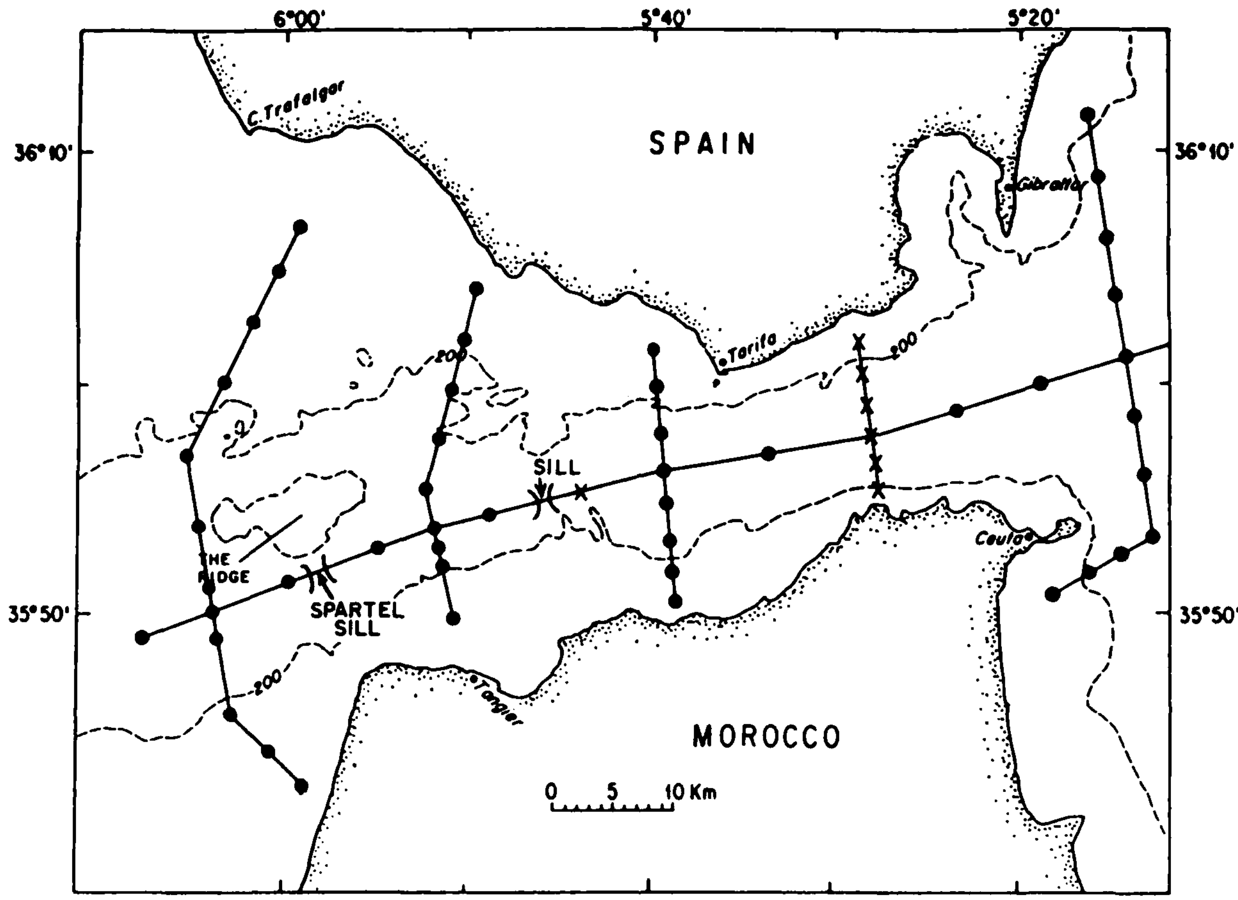


Figure 12. CTD stations to be made during each synoptic hydrographic survey in October 1985, January, March-April, July and October 1986. The along-strait section is to be occupied at the beginning and end of each cruise. Each of the cross-strait sections will be occupied, followed by time series stations over the bottom-mounted profiling current meter near the sill (denoted by X) and repeated sections across the narrowest section east of Tarifa (denoted by -X-X-X-). Some of the surveys are to be extended into the Alboran Sea and Gulf of Cadiz.

moored time series measurements of temperature, conductivity, bottom pressure and interface depth.

Turbulence and mixing measurements are planned by Drs. Gregg and Farmer on two cruises during October 1985 and April-May 1986. On each of these cruises, rapid sections along the Strait and across the Strait on two control sections and 24-hour time series stations (Figure 13) during both spring and neap tides at various locations along the Strait are planned in order to identify the regions and periods of intense turbulence and mixing. Dr. Gregg plans to tether AMP loosely to a drifting ship in order to measure time series of microstructure intensity in the Atlantic layer, Mediterranean layer and the interfacial region between them at various locations in the Strait. At the same time, Dr. Farmer will use shipboard acoustic measurements to profile the velocity and density structure along the Strait to obtain qualitative portraits (like Figure 6) as well as quantitative assessments of the turbulence and mixing in the Strait.

Measurements of nonlinear processes are planned by Drs. Armi and Farmer for a cruise during April 1986 to investigate the internal hydraulics of the two-layer exchange through the Strait of Gibraltar. Rapid transects will be made along the axis of the Strait and across the Strait on control sections to identify regions where the composite Froude number achieves critical, supercritical and subcritical values. On these rapid transects, Dr. Farmer will use shipboard acoustic measurements to profile the velocity and density structure and Dr. Armi will deploy XSVT's and XBT's to associate temperature and salinity properties with features on the acoustic portraits. At the locations of hydraulic control, time series

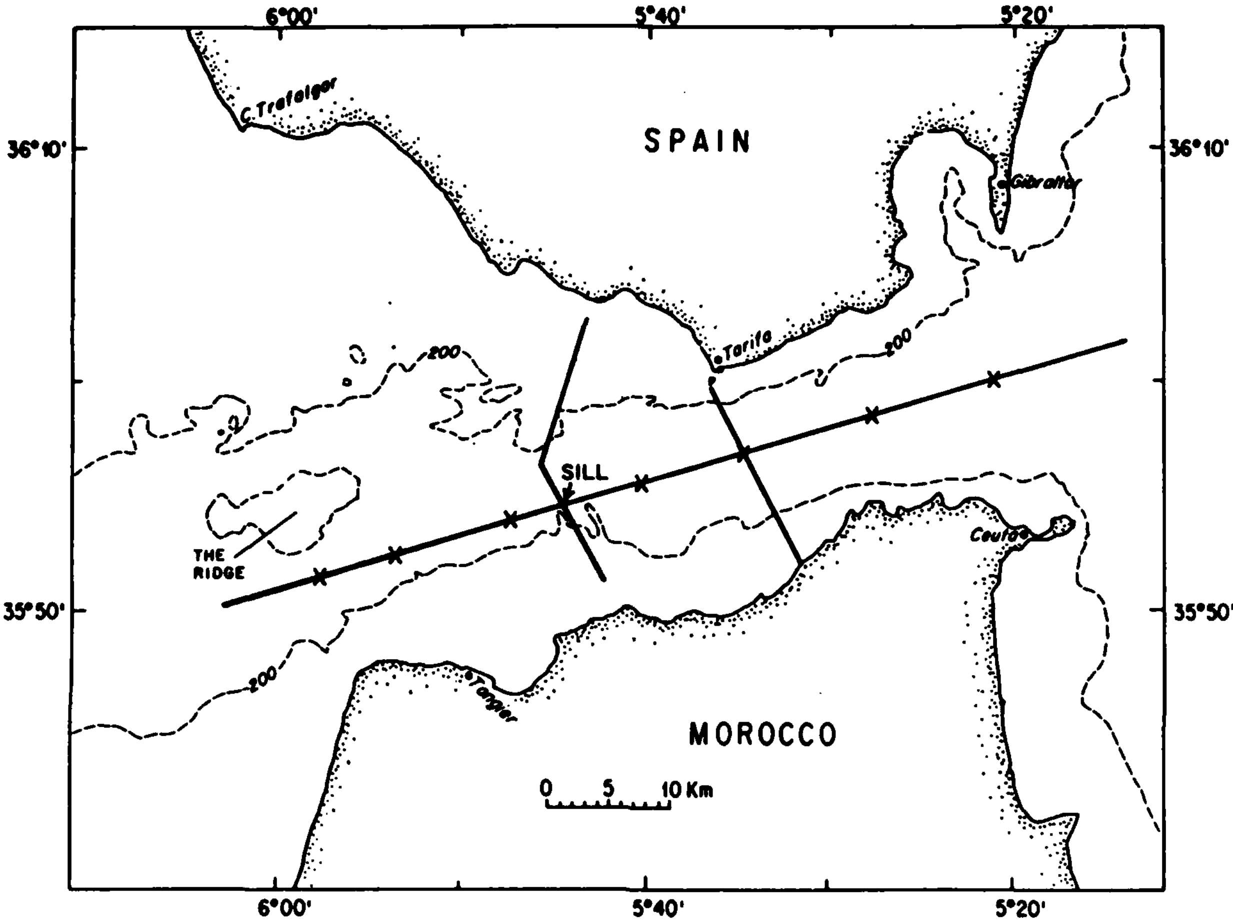


Figure 13. Synoptic measurements of turbulence, mixing and nonlinear processes to be made in October 1985 and March-April 1986. Rapid along-strait and across-strait sections of acoustic profiling, XBT and XCTD stations, and XCP measurements are planned for both ebb and flood portions of the semi-diurnal tides during both spring and neap tides. Time series stations of AMP, CTD, and acoustic profiling are to be made over 24-hour periods at critical locations denoted by X.

CTD stations over a diurnal tidal cycle during both spring and neap tides will be made to describe the spatial and temporal structure of the nonlinear processes controlling the exchange through the Strait.

Aircraft measurements of the atmospheric boundary layer are planned by Dr. Dorman during March-April 1986 in order to understand whether the land station values of wind stress and atmospheric pressure, which may be shielded for certain wind directions by the rugged mountains on either side of the Strait, are representative of conditions in the Strait. Synthetic aperture radar measurements of the sea surface from aircraft are planned by Dr. Richez during March-April 1986 in order to quantify the sea surface signature of the groups of internal solitary waves which regularly propagate from the Strait eastward into the Alboran Sea and which may carry an appreciable fraction of the inflow transport (Kinder, 1984). Radar monitoring of the internal wave fronts at the eastern entrance to the Strait will be coordinated by Dr. LaViolette.

VCTD and AMP measurements are planned by Drs. Perkins and Saunders in the Alboran Sea in May 1986 in order to follow the inflowing Atlantic water as it exits the eastern end of the Strait and begins to circulate anticyclonically in the Alboran gyre. Profiling the Atlantic water as it circulates should provide estimates of how fast it mixes with Mediterranean water and how many times it circulates before continuing eastward past Alboran Island.

Remote sensing measurements from satellite of the size and strength of the Alboran gyre will be collected by Drs. LaViolette and Arnone during the course of the year-long experiment. Relating the measurements of the

inflow and outflow through the Strait to the size and strength of the gyre may help to elucidate the dynamical processes which create and maintain this permanent gyre.

This combination of moored time series measurements and synoptic experiments constitutes the Gibraltar Experiment. Analysis of these measurements should advance our understanding of the dynamics of two-layer flow through a narrow and shallow strait and how it controls the exchange between the two connected basins and should lead to the development of realistic models of the flows through the Strait of Gibraltar.

GIBRALTAR EXPERIMENT SCHEDULE

Basic Principles of Gibraltar Schedule

1. Moored instruments should be in the water as long as possible. One complete realization of the annual cycle is an important objective.

2. Shipboard measurements should be made with most of the moored instrumentation in place. Immediately after mooring deployment (when most instruments will still be working) is the best time for shipboard measurements that do not interfere with the moorings.

3. Extensive expendable (e.g. XBT) drops may foul mechanical instruments (most current meters will be Aanderaa Savonius rotor instruments). The best time for expendable drops is just before mooring recovery.

4. AMP (Gregg) should not be operated near current meter moorings, but should be used when bottom-mounted instruments are in place.

Schedule

Deployment Phase - September-October 1985	Ship
1. Deploy sea level gauges (Fernandez de Castillejo, Garcia Moron) Deploy land-based meteorological stations (Beardsley, Limeburner)	
2. Deploy four bottom-mounted profiling current meters (Pettigrew)	Lynch 11-25 October
3. Microstructure measurements - AMP (Gregg) Acoustic profiling and XCTD measurements (Farmer)	Lynch 11-25 October
4. Deploy eight current meter moorings (Milleiro, Bryden, Pillsbury) Deploy six bottom pressure gauges (Winant)	Tofino 7-27 October
5. CTD surveys, Strait and Alboran (Kinder, Parrilla)	Lynch 1-18 November

Winter Phase - January - February 1986	
1. Recover and redeploy one current meter mooring (Pillsbury)	Cornide
2. CTD survey (Parrilla, Kinder)	Cornide

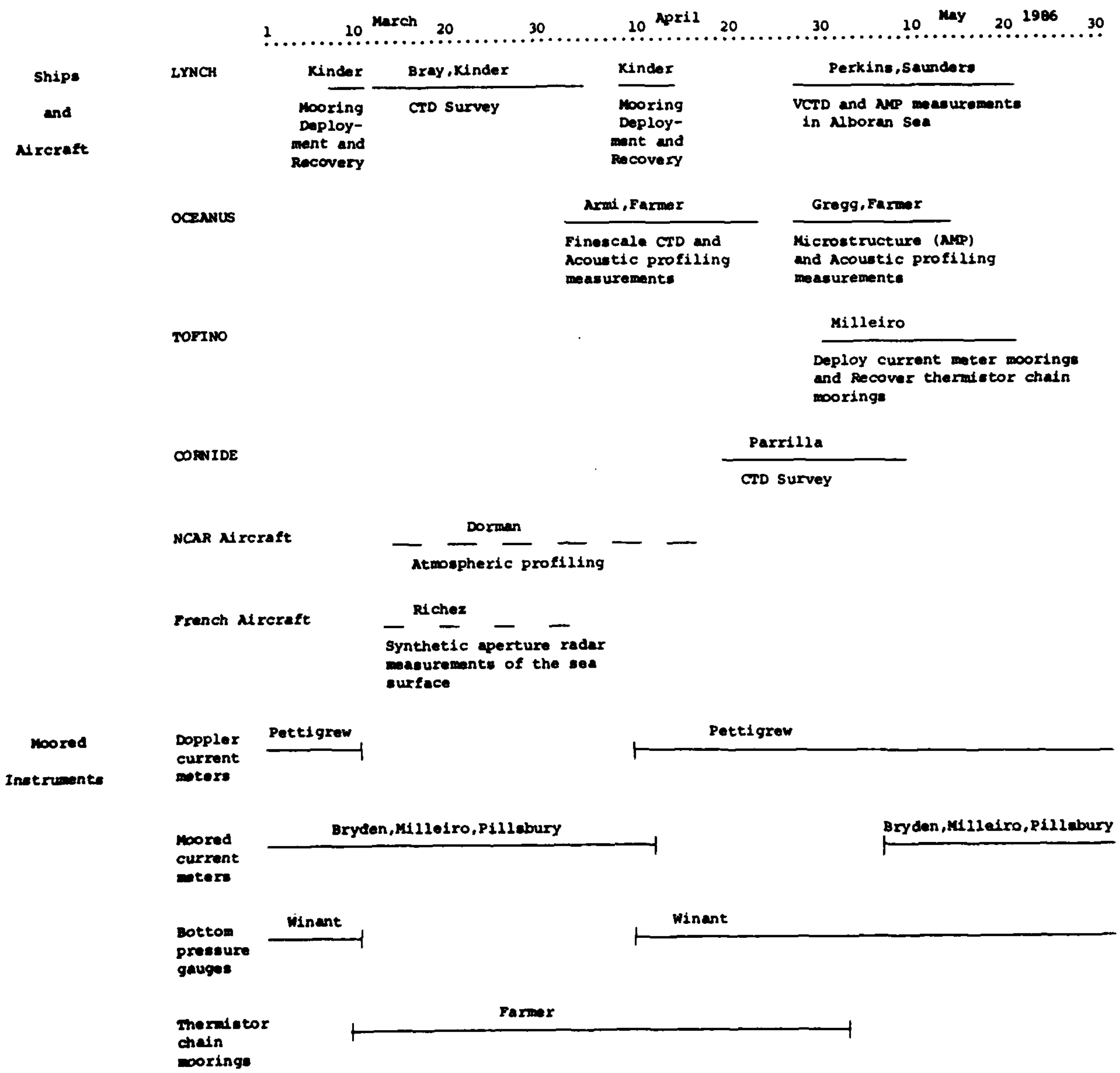


Figure 14. Schedule for Turnaround Phase.

	Turnaround Phase - March - April - May 1986 (Figure 14)	Ship
1.	Recover bottom-mounted profiling current meters (Pettigrew) Recover bottom pressure gauges (Winant) Deploy thermistor chains (Farmer)	Lynch 7-11 March
2.	CTD survey (Bray, Kinder)	Lynch 13 March-4 April
3.	Aircraft atmospheric profiling (Dorman)	NCAR Aircraft
4.	Aircraft synthetic aperture radar measurements of the sea surface (Richez)	French aircraft
5.	Finescale CTD and acoustic current profiling measurements at control sections (Armi, Farmer)	Oceanus 3-23 April
6.	Deploy bottom-mounted profiling current meters (Pettigrew) Deploy bottom pressure gauges (Winant) Recover current meter moorings (Bryden, Pillsbury)	Lynch 9-14 April
7.	CTD survey (Parrilla)	Cornide April-May
8.	Microstructure measurements - AMP (Gregg) Acoustic current profiling measurements (Farmer)	Oceanus 28 April-14 May
9.	Deploy current meter moorings (Milleiro, Bryden, Pillsbury) Recover thermistor chain moorings (Farmer)	Tofino 1-20 May
10.	VCTD and AMP measurements in the Alboran Sea (Perkins, Saunders)	Lynch 28 April-20 May
	Summer Phase - July 1986	
1.	CTD survey (Parrilla, Bray, Kinder) Freon, tritium and trace element measurements (Boyle, Edmond, Roether)	Lynch 17-30 June
	Recovery Phase - October 1986	
1.	CTD survey (Bray, Kinder)	Lynch 16 September-9 October
2.	Recover current meter moorings, profiling current meters, bottom pressure gauges, meteorological stations and buoys (Bryden, Milleiro, Pillsbury, Pettigrew, Winant, Beardsley)	Tofino 10-25 October

Notes on Schedule

1. The expanded sea level network in the Strait has already been established by Garcia Moron and Fernandez de Castillejo.

2. Meteorological buoys should be in place during intensive shipboard measurements in the turnaround phase.

3. During the turnaround phase, there may be other complementary measurements such as:
   a. Radar monitoring of internal wave fronts at the eastern entrance to the Strait (LaViolette);
   b. Drifter deployments in the inflowing Atlantic water (Murray)
   c. Radar measurements of surface currents in the sill region (Richez)

4. During the Gibraltar Experiment there will also be a large-scale experiment in the adjacent Mediterranean entitled "Western Mediterranean Circulation Experiment", coordinated by P. E. LaViolette (NORDA). This experiment includes satellite remote sensing, intensive measurements in the frontal zone north of the Algerian coast, long-term current measurements in the Strait of Sicily, numerical modeling, and other work by investigators from Italy, France, Spain, Algeria, the U. K. and the U. S. Also a large Eastern Medeterranean experiment entitled "Physical Oceanography of the Eastern Mediterranean (POEM)" coordinated by A. R. Robinson (Harvard) and P. M. Rizzoli (MIT) will be underway.

5. The moored current profiler will be deployed during the turnaround phase, and retrieved during the recovery phase. Thus, during October 1985 - April 1986 there will be four bottom-mounted profilers and during April - October 1986 there will be four bottom-mounted and one moored current profilers.

6. Because of the possibility of high wear rates on mooring components, one current meter mooring will be recovered 2 to 4 months after deployment (probably during the winter phase), examined for problems, and then redeployed.

7. The SAR/SLAR flights (Richez) and meteorological flights (Beardsley, Limeburner and Dorman) will be closely coordinated and will occur during CTD surveys.

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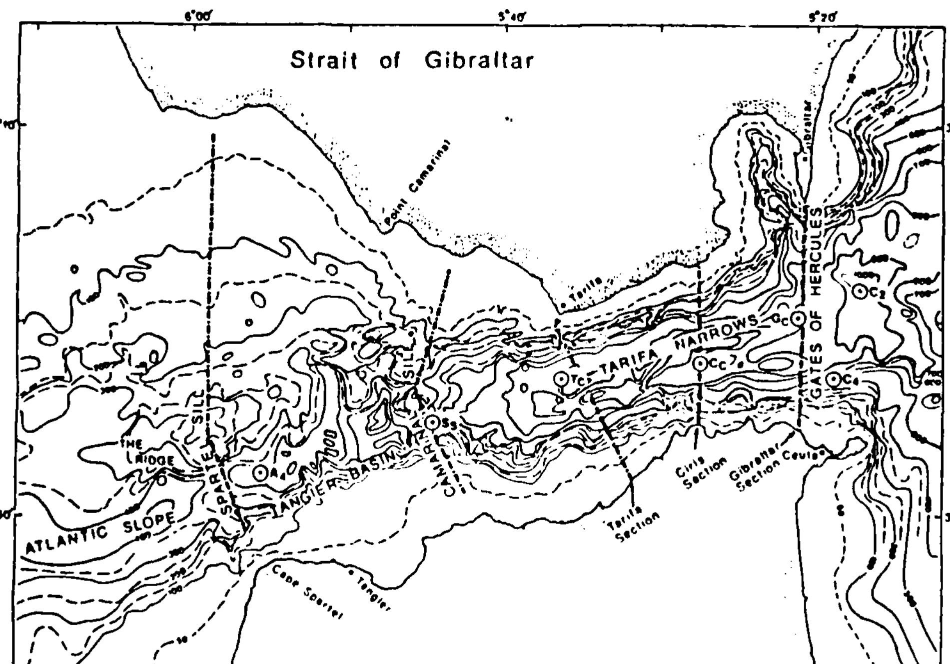
INTERNAL HYDRAULICS L. Armi and D. Farmer

Objectives: To resolve the essential features of the time-dependent internal hydraulic control in Gibraltar Strait and its influence on two-layer exchange between the Mediterranean and Atlantic. The project will focus on the following aspects: (1) The time-dependent structure of flow in the nieghbourhood of the first sill (Camarinal), including (A) the hypothesised supercritical flow west of the sill crest, (B) the internal hydraulic jump connecting to the subcritical conditions in Tangier Basin, (C) the submaximal conditions (i.e. flow reversal of deep layer) over the sill during inflow which is required to specify the exchange throughout the tidal cycle. (2) The internal hydraulic transition between subcritical flow just east of the sill and supercritical flow in the eastern part of the Strait, together with the adjustment back to subcritical flow at the entrance to the Alboran Sea and the response of these features to travelling bores generated near the sill. (3) The behaviour of fronts in the narrow section of the sill. (4) The interpretation of the above processes in terms of internal hydraulic theory and determination of their influence on the exchange of water between the Mediterranean and Atlantic.

Plan: Conduct a sequence of time series measurements at specific locations (Camarinal sill, Tarifa narrows, eastern end of Strait), and a sequence of traverses along the axis of the Strait and across the Strait, taking measurements of the density, velocity and acoustic backscatter profiles. During the October 1985 cruise, the work will be done in conjunction with M. Gregg. Preliminary data collected on this cruise will be used to test measurement procedures and identify optimum sampling schemes, as well as to identify some of the key hydraulic features indicated above. The second cruise in April 1986, will focus on acquisition of a detailed description of the spatial and temporal structure of the hydraulics, aimed at resolving the exchange problem (i.e. objective 4). In addition to the profiling measurements, we will also be deploying moored thermistor chains and current meters. The precise locations are to be determined following analysis of results from the October cruise. The purpose of this short term (1 month) deployment is to acquire current and temperature profiles with sufficient temporal resolution to describe the time-dependent hydraulic response.



METEOROLOGICAL MEASUREMENTS by R. C. Beardsley, R. Limeburner and C. Dorman

Objectives: In order to test the hypothesis that transport fluctuations in the Strait are partially driven by regional wind events and/or differences in atmospheric pressure between the Sea of Cadiz and the Western Mediterranean (Lacombe and Richez, 1982), we plan to deploy several coastal and moored meteorological stations to collect one-year long high-quality time series observations of wind speed and direction, atmospheric pressure, and other atmospheric variables. These time series measurements will then be used with other meteorological observations to examine the synoptic and mesoscale structure of the atmospheric forcing in and near the Strait and to investigate through both event and statistical analyses the possible relationships between transport variability in the Strait and atmospheric variability.

One prime objective of this component is to describe the surface wind and pressure fields in and near the Strait during the oceanographic field program. Although existing coastal meteorological stations provide time series measurements of these variables around the perimeter of the western Mediterranean and Gulf of Cadiz and Bendall (1982) suggests an empirical relationship between wind strength at Gibraltar and the difference in air pressure at Alicante and Casablanca, additional observations are needed to establish accurate quantitative relationships between the regional wind field within and near the Strait and the larger scale surface wind and pressure fields.

Plan: To obtain these measurements, we propose to deploy a moored meteorological buoy just west of the Strait in the Gulf of Cadiz, a shore-based meteorological station on the Isle of Tarifa within the Strait, a shore-based meteorological station on the coast of Morocco within the Strait, and a moored meteorological buoy just east of the Strait in the Alboran Sea. This array is designed to obtain high quality time series observations of (a) the near-surface wind on both sides of the Strait and in the high speed cores of the surface air flow in the Alboran Sea and Gulf of Cadiz during strong wind events; and (b) the atmospheric pressures and pressure difference between the Gulf of Cadiz and Western Mediterranean. Clive Dorman is planning a series of short term surface soundings of the marine layer in the Strait during high wind events in early spring, 1986, to focus on how the constricted coastal topography influences the response of the marine layer to external atmospheric forcing.

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Bendall, A. A., 1982. Low-level flow through the Strait of Gibraltar. Meteorology Magazine, 14, 149-153.

Lacombe, H. and C. Richez, 1982. The regime of the Strait of Gibraltar. In: Hydrodynamics of Semi-Enclosed Seas, J.C.J. Nihoul, editor, Elsevier, New York, pp. 13-73.

SEASONAL VARIABILITY IN THE FLOW THROUGH THE STRAIT OF GIBRALTAR

Myriam Bormans, Chris Garrett and Keith Thompson

Historical sea level data show a seasonal cycle in the surface inflow into the Mediterranean, with more than average surface inflow in the first half of the year, less than average in the second half. We are studying the relationship of this seasonal cycle to various other environmental parameters, such as wind and the density of the incoming Atlantic and outflowing Mediterranean water, using regression techniques and simple models. This study of the long records of historical data will tell us how representative the 1985-86 experiment is, and understanding the seasonal cycle may help to confirm or disprove models being used for the mean flow.

TRACE ELEMENT MEASUREMENTS E.A. Boyle

Objectives: Trace metal measurements are being undertaken to understand the persistence and sources of the trace metal plume first observed in the Alboran Sea in June, 1982. This plume may be an important source of the excess trace metals which have been observed in the Mediterranean Sea. Since trace metal signatures of different water sources may be distinct, these measurements also may help to provide constraints on the origen of inflowing waters.

Plan: Surface water trace metal samples will be collected (on a space and time available basis) along most of the hydrographic transects of Kinder, Bray, and Parilla. During the April 1986 hydrographic work, shallow water stations will be occupied along the track and surface samples and profiles in the continental shelf waters of Spain will be undertaken. The April work will occupy one day of ship time, which can be dispersed throughout the entire cruise. The working area will be similar to that depicted on Kinder's hydrographic chart, and will also include waters on the Atlantic Spanish continental shelf.

TRANSPORT OF HEAT AND SALT THROUGH THE STRAIT OF GIBRALTAR - N. Bray

Objectives:

1) Estimate from moored time series of velocity, temperature and conductivity the low frequency fluctuations of heat and salt flux through the Strait.

2) Determine from CTD surveys the horizontal and vertical distribution of the water masses involved in both the inflow and the outflow.

3) Combining 1) and 2), construct a description of the water mass components of the low frequency heat and salt exchange through the Strait.

Components of the Experiment:

1) Moored conductivity measured at all pressure gauges (with C. Winant).
2) Moored conductivity measured at all Anderaas (H. Bryden, D. Pillsbury).
3) Large-scale CTD surveys of the Alboran Sea and the Gulf of Cadiz (see inset A).
4) Small-scale CTD surveys of the Strait proper, including conductivity sensor <u>in situ</u> calibrations (see inset B and abstracts of T. H. Kinder and G. Parilla).
5) Time series stations near the sill at spring and neap tides to illustrate the effects of strong tidal currents on the hydrographic sections.

The mooring component will cover the entire year of the field program. The hydrographic work will be carried out during the turnaround and recovery phases (April and October, 1986).

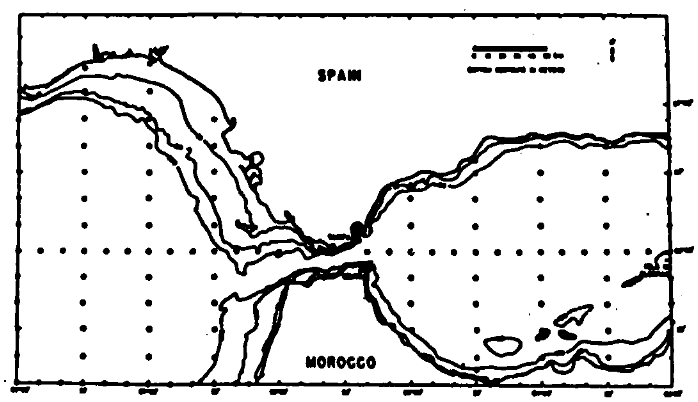


Figure 3. Large-scale survey plan.

(A)

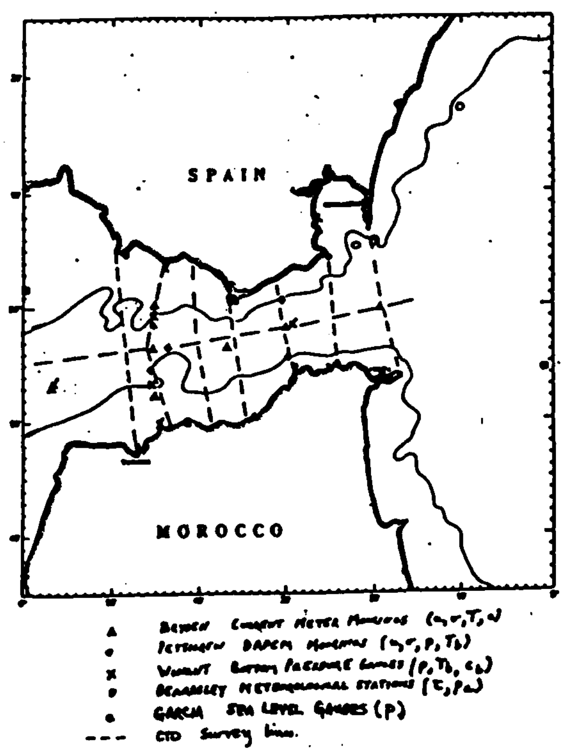


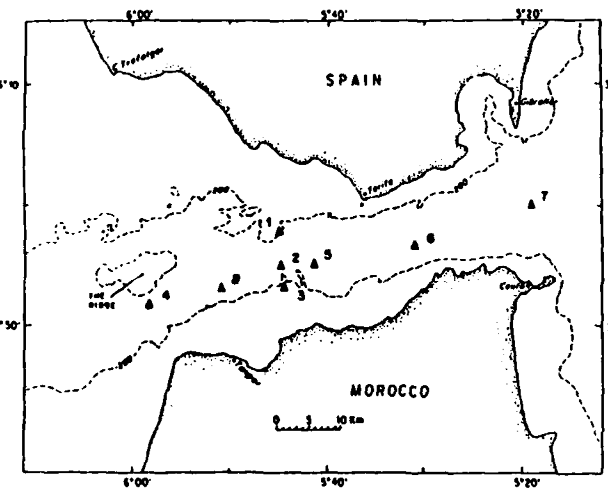
Figure 4. Small-scale survey plan, superimposed on the most recent moored instrument plan.

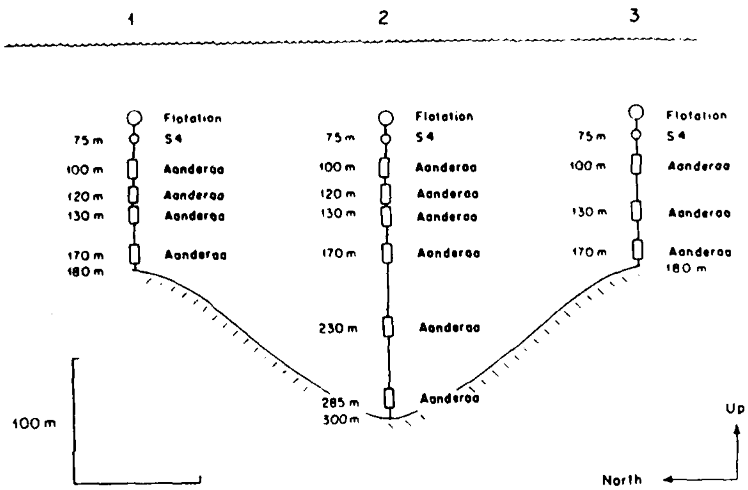
(B)

GIBRALTAR EXCHANGE MEASUREMENTS

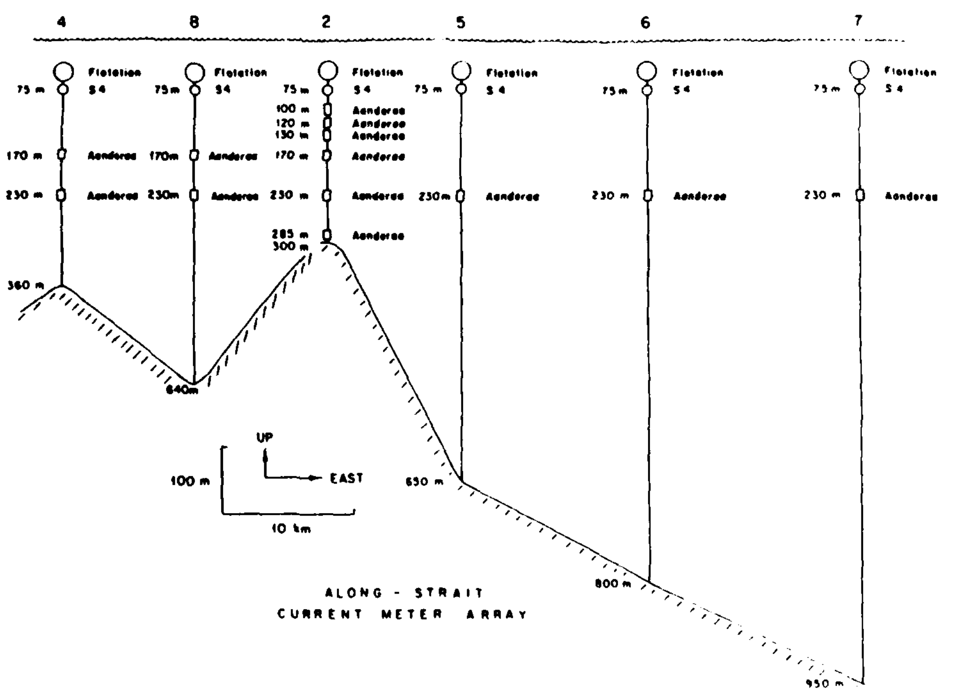
H. Bryden, C. Milleiro, D. Pillsbury

A three-dimensional array of current, conductivity, temperature and pressure measurements will be deployed in the Strait of Gibraltar (Figures 1, 2, 3) during October 1985. The array would be recovered after six months during April 1986 and redeployed. The array would be finally recovered in October 1986 so that a year-long set of measurements is obtained. This array has three principal objectives: to make good estimates of the exchange across the sill section; to determine the cross-strait structure of the velocity in both the Atlantic and Mediterranean layers and of the interface between the layers; and to examine the along-strait propagation characteristics of fluctuations in the Atlantic and Mediterranean layers.





CROSS - STRAIT
CURRENT METER ARRAY



ALONG - STRAIT
CURRENT METER ARRAY

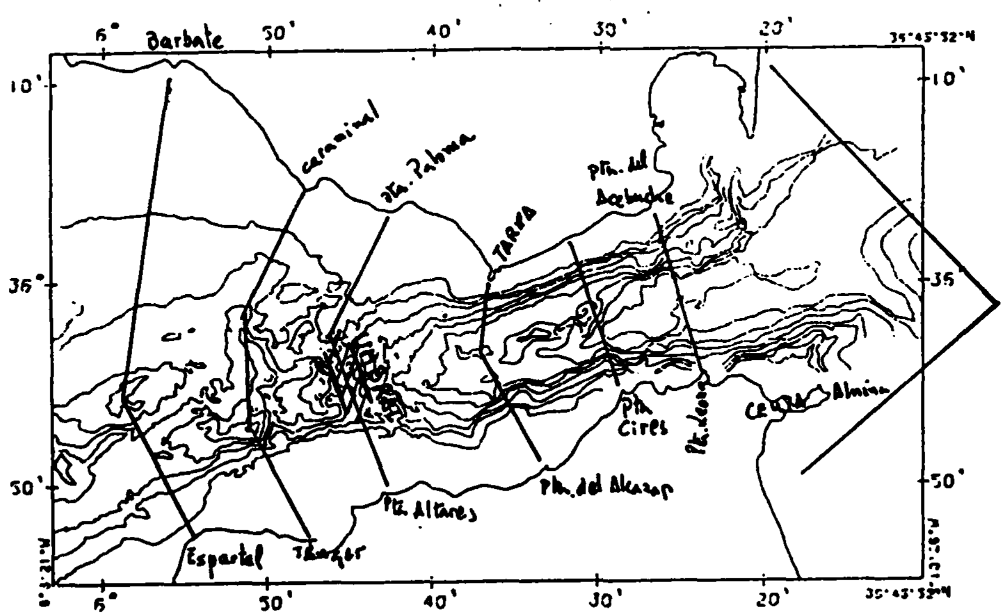
OCEANOGRAFIA QUIMICA   José M. Cabanas, José G. Braun, M. Deya

Objetivos.- Se plantea el estudio de la distribución y variaciones de oxígeno, nutrientes, materia en suspensión, penetración de luz y clorofila; con posible opción a determinar metales pesados en sedimentos, en el Estrecho de Gibraltar y zonas adyacentes.

Todo ello muy vinculado al estudio físico del área, para lograr:

1.- una explicación de la dinámica de la zona.
2.- Hacer un balance de materia que pasa a través del Estrecho.
3.- Cuantificar el flujo de agua Mediterránea que sale y Atlántica que entra; sus características y su influencia en otras latitudes (Galicia, Canarias, Baleares) en colaboración con otros proyectos en curso.

Plan de trabajo.- En conjunción con las campañas de Física, se pretende hacer un muestreo de los parámetros indicados anteriormente en las estaciones señaladas en el mapa adjunto.

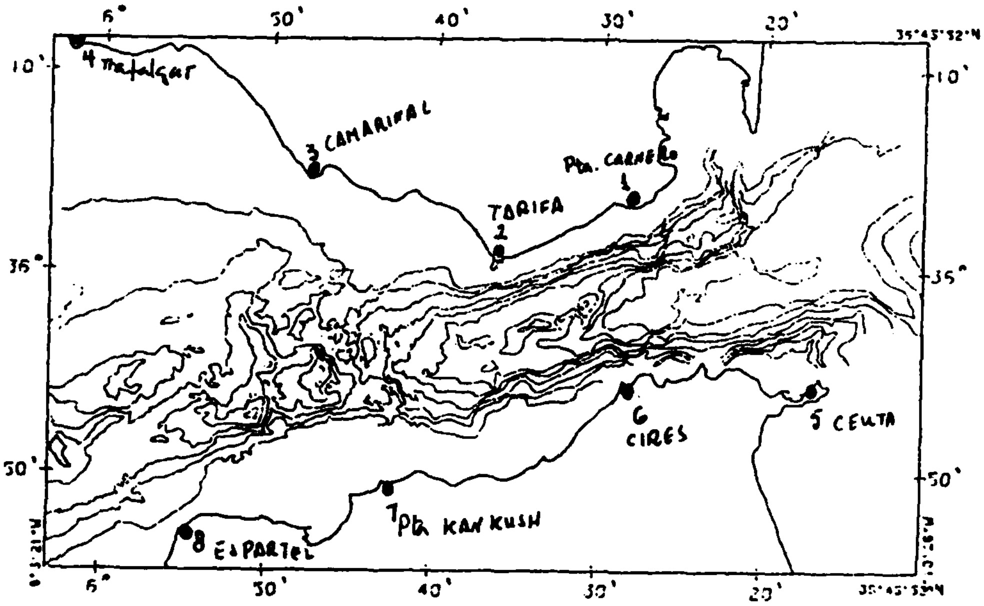


NIVELES MEDIOS EN EL ESTRECHO

Federico Fernández, J. García,
Mª J. García

<u>Objetivos</u>.- 1) Análisis armónico de mareas registradas en Ceuta, Tarifa, Trafalgar y Pta. Carnero, 2). Correlación entre ellas y mapa lineas cotidales y corango, 3). Variación de los niveles medios en periodos relativamente cortos - (órden de 1 a 3 meses).

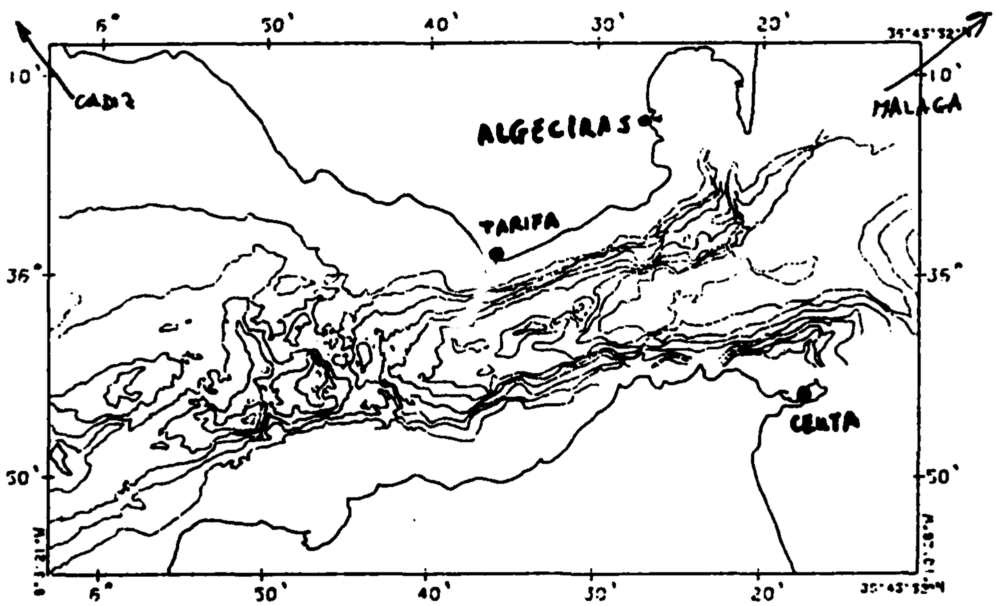
<u>Plan</u>.- La recolección de datos empezó en Septiembre de 1983 estableciendo sensores de presión en varias localizaciones en las cartas africana y española del Estrecho (véase mapa adjunto). Algunos llevaban acoplados sensores de S y T y en algunos puntos se montaron tambien estaciones meteorológicas.
Todas las estaciones no fueron ocupadas al mismo tiempo sino que se cambiaban al cabo de varios meses, pero se procuró que las medidas fueran simultáneas en ambas orillas del Estrecho.
El trabajo de campo acabará en Abril y se podrá disponer de un informe preliminar para después del Verano.
Este programa ha sido financiado por SECEG.



MAREAS EN GIBRALTAR José Mª García Morón, José L. López

Objetivos. - A) Estudio de las variaciones del nivel del mar en el Estrecho de Gibraltar y su relación con el flujo existente en el mismo, utilizando los registros de marea en las estaciones mareográficas permanentes del I.E.O., de Tarifa, Algeciras y Ceuta, complementadas con las de Cádiz y Málaga.
B) Correlación de estas variaciones de nivel con las perturbaciones meteorológicas.

Plan. - Como ya se ha mencionado, para este estudio se utilizarán los registros de marea del I.E.O. que serán complementados con los datos meteorológicos del Instituto Nacional de Meteorología. Pero se considera prioritario establecer nuevo instrumental en dos puntos de la costa, en ambas partes del Estrecho, Ceuta en una, y Tarifa o Algeciras en otra, para obtener simultáneamente las variaciones del nivel del mar y los parámetros presión atmosférica, velocidad y dirección del viento.

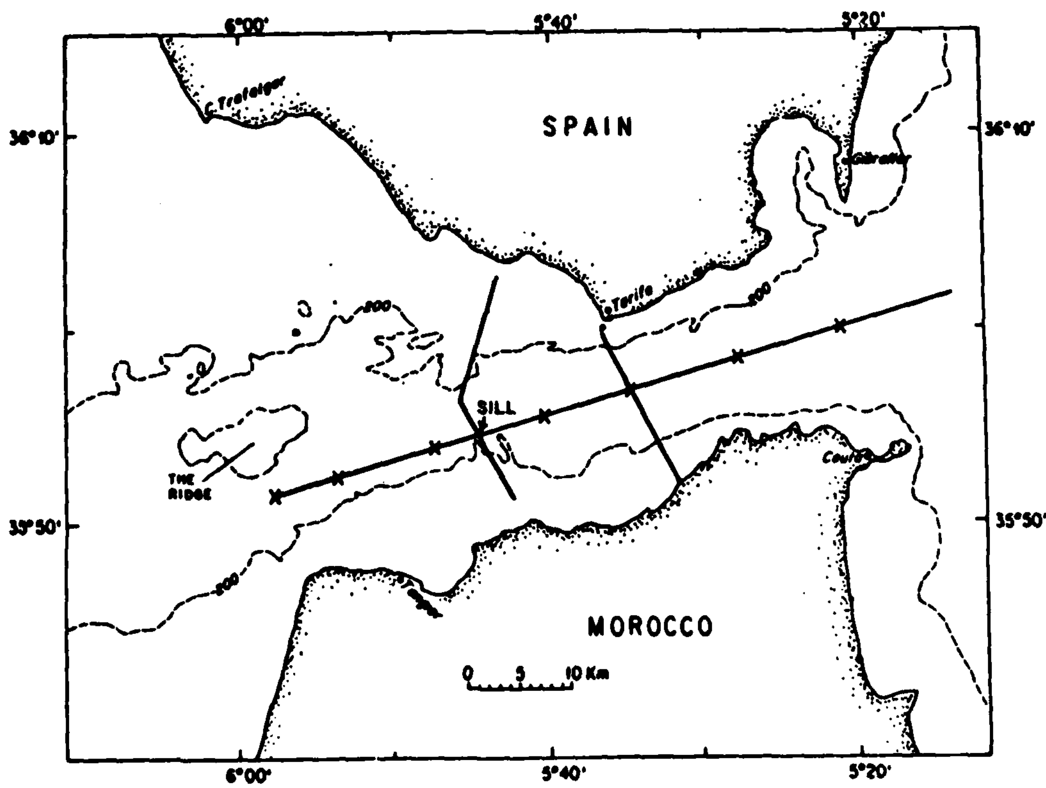


TURBULENCE AND SHEAR MEASUREMENTS M. C. Gregg and W. E. Nodland

Objectives: Measurements of turbulence are needed to understand how mixing affects the dynamics of flow in the Strait and to quantify the modification of the water masses flowing through the Strait. Shear measurements are needed to understand and describe the dynamics of flow through the Strait and to provide a background for interpreting the turbulence.

Turbulence profiles will be made using the Advanced Microstructure Profiler (AMP), which can fall freely to 300 m while attached to the ship with a 2 mm diameter Kevlar cable containing a fiber optic data link. Mounted on the AMP are: 2 shear probes for measuring velocity microstructure, a fast thermistor and a cold film for measuring temperature microstructure, a Neil Brown conductivity cell and a thermistor for conductivity and temperature, and 2 accelerometers for monitoring vehicle motion. The tether to the AMP permits taking repeated profiles in order to average over the intermittence of the turbulence.

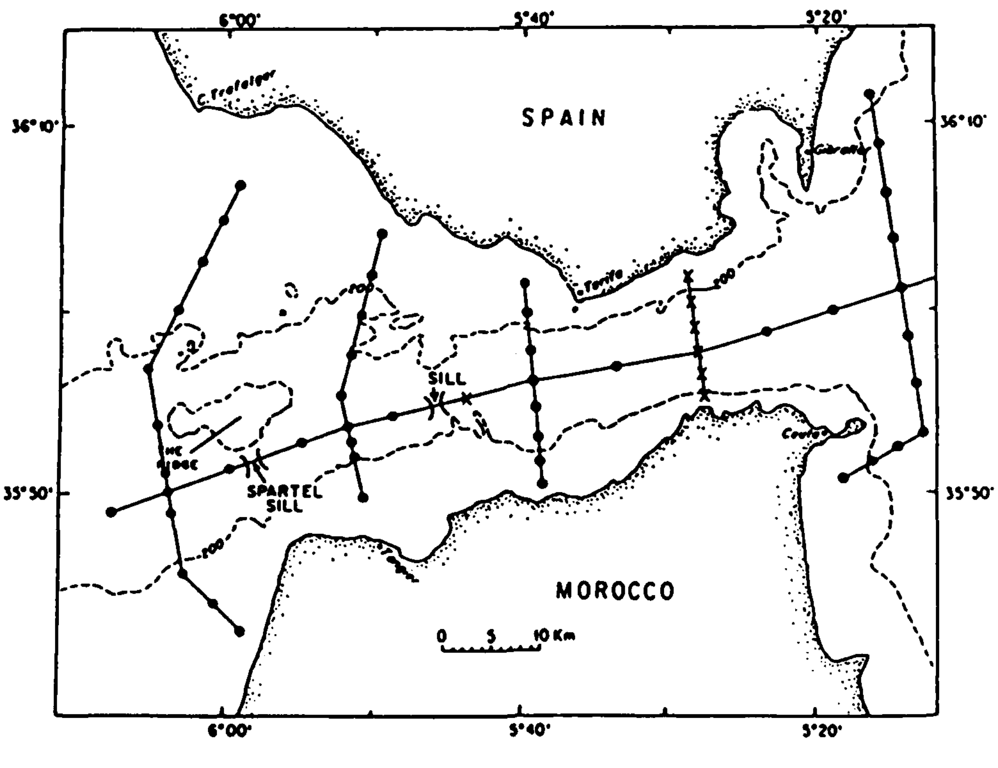
Plan: Time series of microstructure intensity in the Atlantic water, Mediterranean water and the interfacial region between them will be made at various locations along the Strait and across the control sections to identify the periods and locations of intense turbulence and mixing and to quantify the modification of water masses in the Strait. If heavy ship traffic or bad weather force us out of the Strait, we plan to make time series through the train of internal waves which propagate eastward into the Mediterranean from their generation region in the Strait.



HYDROGRAPHIC MEASUREMENTS T. H. Kinder and D. A. Burns

Objectives: The CTD hydrographic measurements will provide a spatial framework and background for the point measurements. Specifically, the CTD data will: (1) Provide trasport estimates from sections outside the Strait that are independent of those inferred from the moorings; (2) Provide estimates of rotational effects from high resolution cross-strait sections; (3) Elucidate the presence of intermediate and deep Mediterranean waters, their mixing, and their paths, with near-bottom (< 10 m) and accurate (Neil-Brown) data; (4) Permit assessment of the sources of the inflowing Atlantic Water; (5) Measure seasonal changes in stratification throughout the Strait; (6) Provide estimates of mixing between Atlantic and Mediterranean Waters; (7) Calibrate the delineation of the density field by the profiling current meters (Pettigrew); (8) Link the Strait to the Mediterranean outflow study (Price, Stanford, and Lueck) and to the Alboran Sea study (Parrilla); and (9) Provide data for heat and salt budgets (Bray).

Plan: Occupy the grid of 5 cross-Strait and 1 along-Strait sections (figure) at least once during each experiment phase (e.g., deployment and turnaround). Do a time series (13-25 hours) at the sill near the profiling current meters and across the Strait at Point Cires. The grid and time series will require 4-6 days; if ship time is available, the pattern will be repeated so that it is done once at spring and once at neap tide. I may deploy a small drogue (about 50 m depth) and follow it through the Strait to measure the evolution of a water parcel.



CTD stations to be made during each synoptic hydrographic survey in October 1985, January, March-April, July and October 1986. The along-strait section is to be occupied at the beginning and end of each cruise. Each of the cross-strait sections will be occupied, followed by time series stations over the bottom-mounted profiling current meter near the sill (denoted by X) and repeated sections across the narrowest section east of Tarifa (denoted by —X—X—X—). Some of the surveys are to be extended into the Alboran Sea and Gulf of Cadiz.

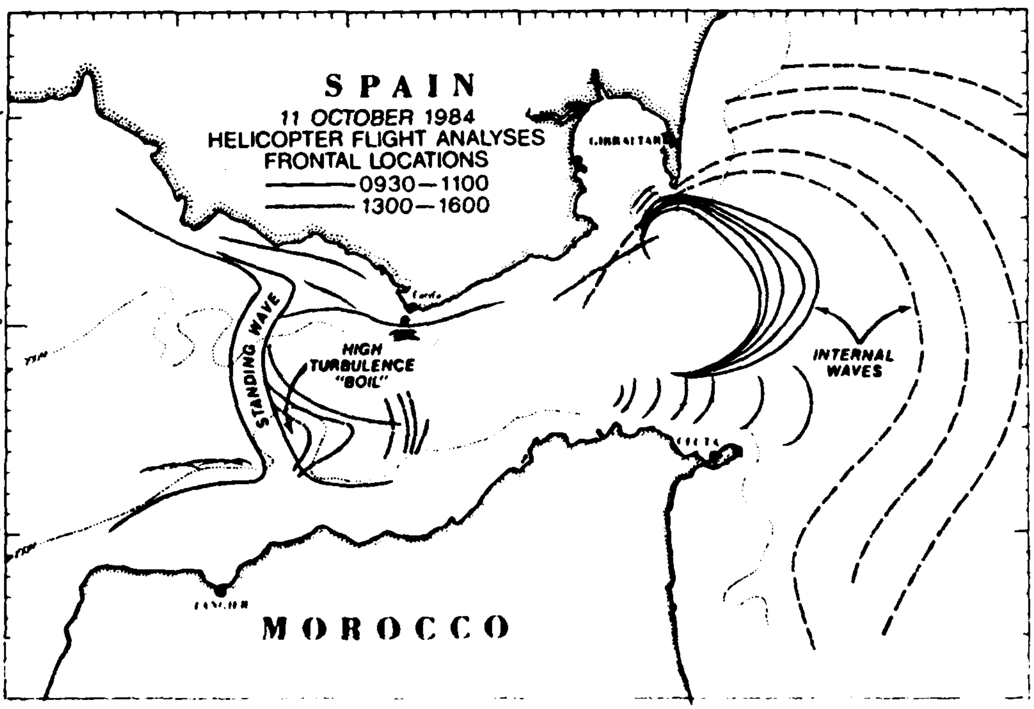
A Preliminary Study of a Standing Internal Wave in the Western Approaches to the Strait of Gibraltar

Paul E. La Violette and Robert A. Arnone

Aircraft flights during the period 6-11 October 1984 provided data which indicate a standing internal wave was continuously present west of the Strait of Gibraltar at 5°50' West. Although the wave appeared to essentially remain at one location-stretching from Spain to Morrocco, its surface appearance--visually and in the aircraft radar and infrared scanner imagery--showed considerable changes in strength that took place within several hours. The surface feature of the wave varied in appearance. However, it normally was shown to have a main portion that consisted of a central 1 kilometer-wide ridge of rapidly moving water with almost no waves. On each side of this central region, the waters were usually agitated with a strong chop. On one occassion the sea state in this region caused a wave to go over the 20 meter high afterbridge of a 100 meter long freighter at the point that the freighter left the center comparitively calm area and entered the chop.

AXBT's data showed that horizontal changes of 3°C were present across the feature and that vertical disturbances in temperature extended at least to the depth of the AXBTs (350 meters). Examination of the regional bathymetric charts shows the standing internal wave was associated with the main sill of the Strait of Gibraltar and was evidently a manifestation of the Mediterranean intermediate water flowing westward at depth over the sill into the Atlantic.

Unlike the eastward-moving tidal-induced internal waves normally found in the strait that displayed eastward-oriented bows as their surface configuration, the standing internal surface wave appearance was that of a large westward-oriented bow. On two occasions, eastward-propagating sets of tidal-induced internal waves were found originating from a position south of the center of the standing wave. Although numerous eastward-moving internal waves were seen in the straits during the flights none was noted west of the standing wave.



INTERNAL WAVES AND HYDRODYNAMIC MODELING

D. Ouazar, M. Annaki, A. Benabdeljelil, N. Benmansour

The main aims of the Gibraltar Experiment are:

i) to define the magnitude of the exchange between the Atlantic and Mediterranean basins and their variations over tidal to seasonal time scales;
ii) to assess directly the effects of rotation, friction, mixing and other nonlinear processes;
iii) to define an efficient method for long-term measurement of the flows through the Strait so that their interannual variability can be monitored.

Of particular concern for this project are:

i) internal waves
ii) modeling of the residual circulations and flow
iii) the interface layers
iv) the shear effects.

INTERNAL WAVES

OBJECTIVES

Internal waves occur within subsurface layers of marine waters that are stratified because of temperature and salinity variation-. It is known that these waves can significantly influence oceanic current measurements, undersea navigation, antisubmarine warfare operations, and even the feeding habits of the marine animals. The observations (straits of Gibraltar, Georgia, Andaman sea) show some asymmetries in the characteristics. These phenomena are governed by nonlinear partial differential equations. Experiments must be undertaken to complete information and to verify the mathematical modeling.

PLAN

As above-mentioned, an internal wave measurement program in the Strait of Gibraltar must be undertaken with

- current meters at several depths
- expendable bathythermographs
- conductivity, temperature and depth (CTD)
- satellite observations (if possible).

HYDRODYNAMIC MODELING

OBJECTIVES

i) Study of the dynamics of flow through a narrow and shallow strait.
ii) Hydraulic control problems with two layers
iii) Location of the interface between Atlantic and Mediterranean seas.

PLAN

Experiments must be carried out using sea-level gauges, current meters, bottom pressure gauges, thermistor chains, CTD, XBT, XDP, VCTD.

OCEANOGRAPHIC SURVEYING

OBJECTIVES

Altimetric connecting of two sea-level gauges on the Moroccan and Spanish banks by oceanographic surveying.

PLAN

Measurement of longitudinal velocities in the Strait of Gibraltar.

HIDROGRAFIA Gregorio Parrilla, Rafael Molina

Objetivos.- Las medidas hechas con el CTD servirán para los siguientes objetivos: 1). Ayudar al conocimiento de la relación entre los fenómenos que ocurren en el Estrecho y aquellos en el Mar de Alborán (Parrilla) y con la salida de agua mediterránea (R. Molina). 2). Aclarar el origen y composición de las masas de agua que intervienen en el intercambio de flujos a través del Estrecho. 3). Variabilidad de la estratificación de las masas de agua en el Estrecho (variación de la pendiente transversal y longitudinal de la superficie de separación). 4). Apoyar las medidas de los correntómetros y similares ayudando a definir los campos de salinidad y temperatura; utilización de estos en la estimación del transporte; e interactuar con las medidas de los parámetros químicos.

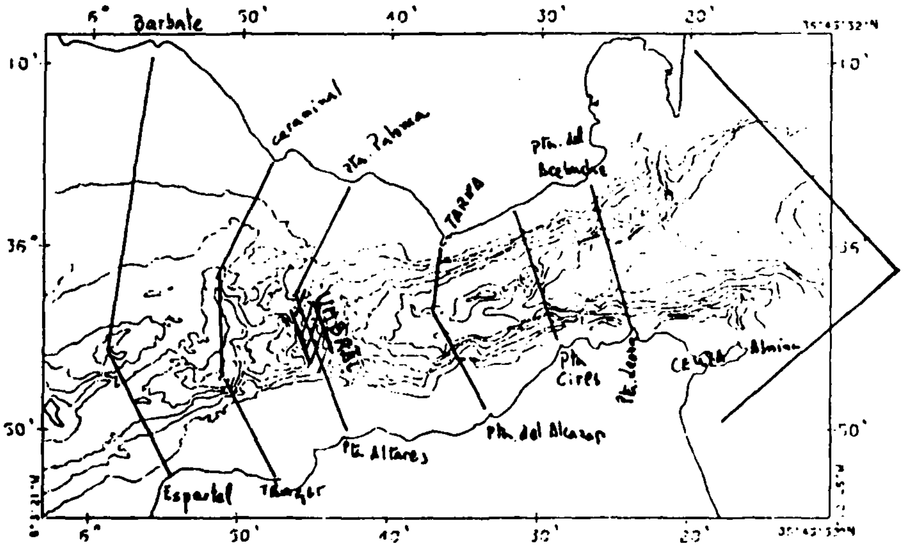
Plan.- Se han seleccionado 7 secciones transversales posibles más 1 longitudinal. De las transversales habrá que seleccionar un número inferior y/o sustituir algunas de ellas por una estación fija (24 horas mínimo). La elección de las secciones o su cambio por estaciones fijas depende de cómo se vaya desarrollando el trabajo: tiempo que se tarde en recorrerlas, ritmo de bajada del CTD, seguridad, etc. Por ello si podemos realizar una primera campaña en Junio de 1985 la usaríamos como campo de pruebas. Aparte de esta campaña pensamos realizar otra en Octubre a bordo del García del Cid coincidiendo con el fondeo de los diversos correntómetros.

En 1986, hay dos épocas en las que sería importante estar: una es en Enero y Febrero y la otra en Marzo-Abril.

La primera tiene como fin recoger datos en Invierno y la segunda es la época en la que los sistemas de medida de corrientes permanentes serían recobrados para comprobar su funcionamiento y retirar los datos y vueltos a fondear. Durante este periodo es cuando habrá una mayor actividad por parte de todos los participantes. No creo que dispongamos del "Cornide" para dos campañas seguidas, y por otra parte, tampoco somos muchos para efectuarlas. Habrá que esperar a como se desarrollen los acotencimientos.

Por último el trabajo de campo final se realizará en Octubre, cuando se recobrarán todos los correntómetros de una manera definitiva. Quizás se pueda alquilar otra vez el Garcia del Cid.

Además del trabajo própio en el Estrecho queremos tomar datos en sitios específicos del Mar de Alborán y Mar de Cádiz. Esto depende del tiempo disponible.



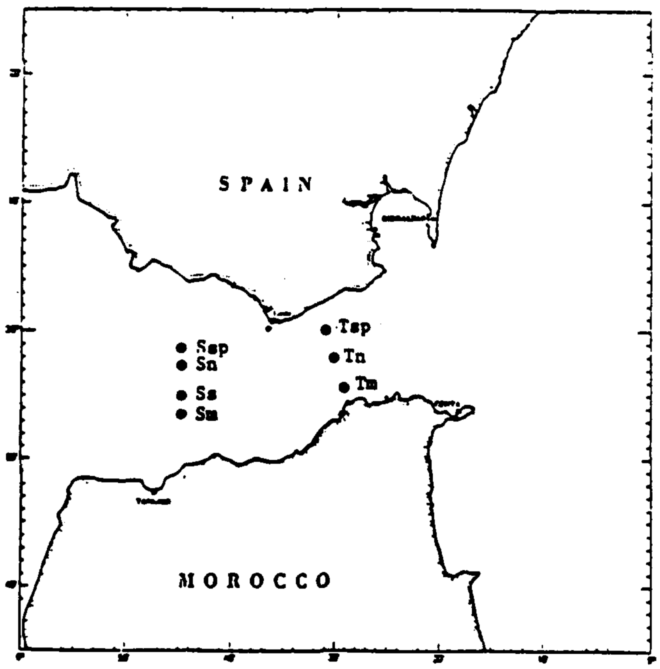
Bottom-Mounted and Moored Doppler Profiling Current Meter Measurements

N.R. Pettigrew and J.D. Irish

Objectives: Doppler Acoustic Profiling Current Meters (DAPCM's) deployed at the Sill and the Tarifa Narrows will provide time series measurements of current profiles, and bottom pressure, temperature and perhaps conductivity. The principal goal of the Doppler program is the investigation of the spatial and temporal flow variability in the Atlantic and Mediterranean layers, and direct measurement of transport. Other specific areas of interest include: 1) The role of meteorological forcing in flow variability; 2) The cross-Strait structure of the vertical profiles of currents; 3) The use of pressure measurements for estimating transport fluctuations in the Strait; 4) Acoustic sensing of the Atlantic/Mediterranean density interface; 5) Direct measurement of vertical velocities associated with internal waves; 6) The spatial and temporal variability of the bottom temperature field and its relation to forcing.

We expect to work closely with other investigators who have similar interests.

Plan: Four bottom-mounted DAPCM's will be deployed in the Strait for 13 months with a mid-experiment turnaround. Locations Ss and Sn (see figure) will be occupied for the entire experiment. The other two bottom-mounted profilers will be deployed at some combination of the shallow sites Ssp, Sm, Tsp and Tm. The final decision on these locations awaits further analysis of the 1984 pilot data of Pettigrew and Bryden. During the latter half of the experiment a fifth profiler will be moored approximately 400m above the bottom in the center of the Tarifa Narrows (Tn).



Approximate locations of the DAPCM deployments. No more than five of these sites will be occupied at one time.

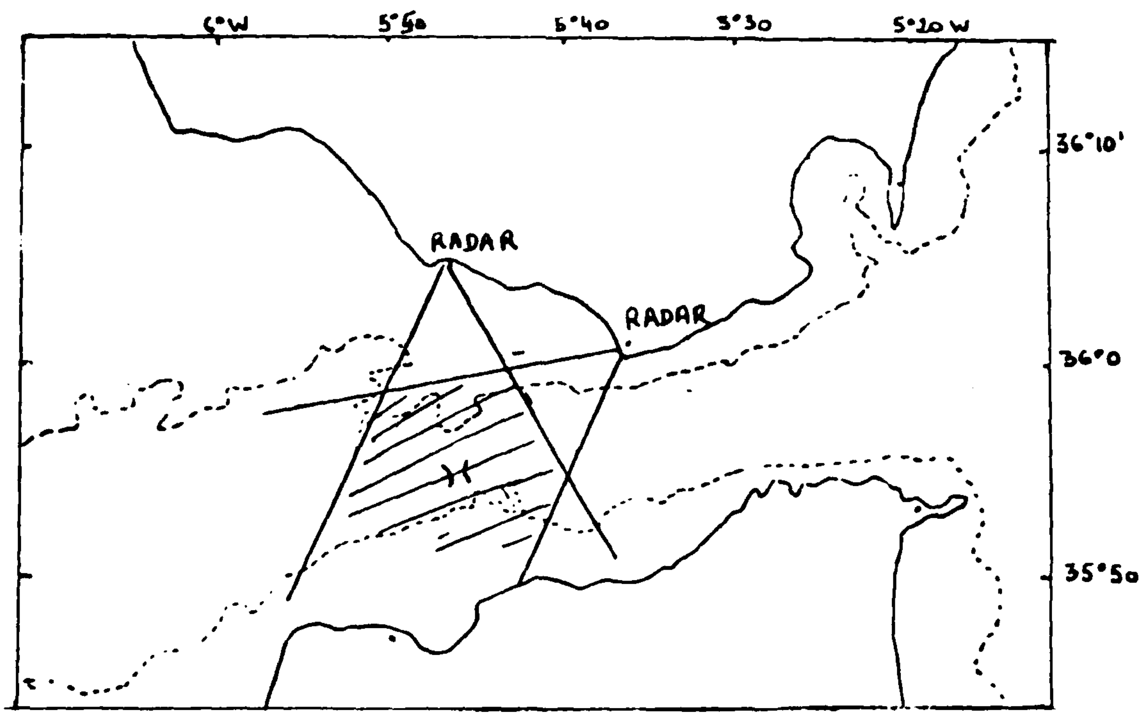
SAR/SLAR AND HF RADAR MEASUREMENTS   C. Richez

Objectives: SAR/SLAR and HF RADARS measurements will allow simultaneous surface observations of currents and internal waves in the Straits of Gibraltar, in particular around the sill area, during tidal cycles.

Plan:

1) SAR/SLAR: The swath of the imaging radar is about 10 km, so we can cover almost the width of the strait in its narrowest section in one passage of 100 km east to west in half an hour. This path could be repeated 6 times, from HW - 6 to HW + 6 during a morning tide, at springs. Since the aircraft cannot fly during more than 12 hours non stop, the effect of the diurnal component of the tide could be explored by repeating this flight 24 hours later, during the next evening tide. For studying the neap-spring tidal effect, we plan two similar surveys, about 15 days later, at neaps. These flights will be correlated with CTD surveys in the strait. The operational aspect will be under the responsibility of the GDTA Toulouse (Cazaux, Lannelongue, Vaillant), and the "Department Radar et Localisation" (CNES/Toulouse). The pretreatment of the radar images will be insured by the "Division Traitement d'Images" (CNES/Toulouse/Duplaa), the extraction of the geophysical parameters will be done by B. Forget (LSEET/Toulon) and the interpretation of the results and their relation with the oceanographic features in the strait, surface current measurements and in situ observations will be insured by C. Richez, H. Lacombe and J. C. Gascard in Paris.

2) HF RADAR: Pr Broche, from the "Laboratoire des Sondages Electromagnétiques de l'Environnement terrestre (LSEET/Toulon-France) will deploy 2 HF radars in the Straits: one could be situated at Tarifa shooting westwards, the second one on a northwestern shore shooting southwards (see figure). It would be possible to monitor the sill area for obtaining maps of surface current vectors during about fifteen days from springs to neaps. For technical reasons, it seems difficult to find other places on the Spanish coast but this could be studied later on, in relation with Spanish labs. Pr Broche will insure the treatment of the results and C. Richez, H. Lacombe and J. C. Gascard will work with him on their geophysical interpretation.

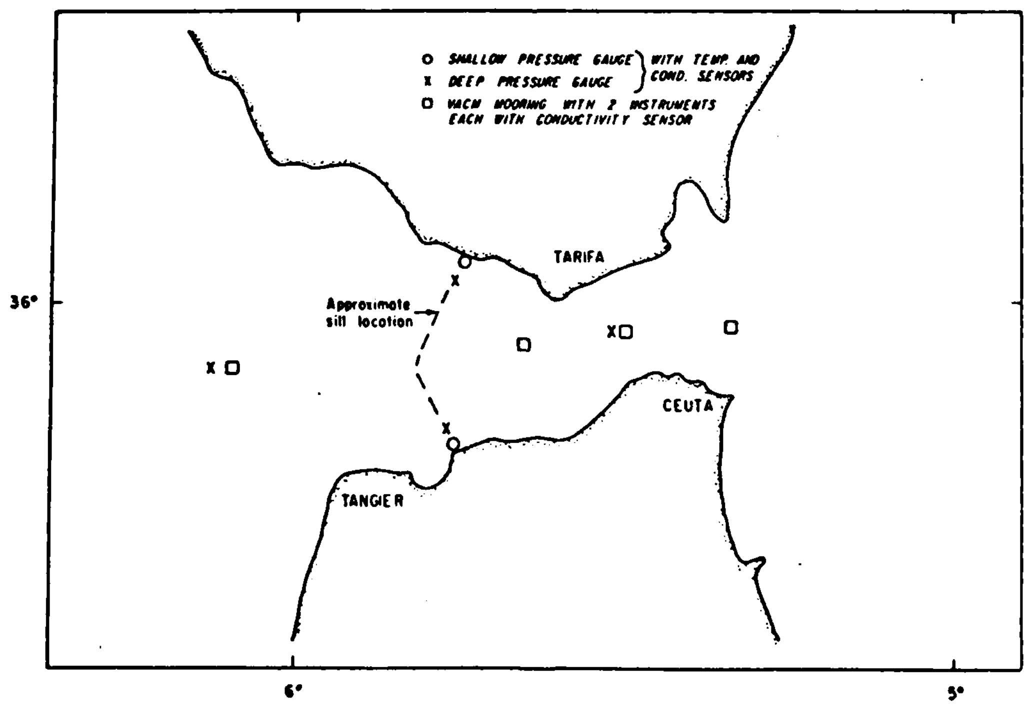


BOTTOM PRESSURE, TEMPERATURE AND CONDUCTIVITY OBSERVATIONS

C. D. Winant, A. Ruiz, J. Candela

Objectives: The general objective of the bottom pressure program is to observe pressure fluctuations in the Strait and relate these to the mass exchange through Gibraltar. Since we will be sampling every minute over a year, we will be able to study a broad range of phenomena going from the low frequency fluctuations (1 cycle/month) to the high frequency tides (6 cycles/day). In the low frequency range our objectives are: (1) to determine what is the structure of the pressure field, the density field and sea level; (2) to test by comparison with mass flux estimates obtained from the current meters whether the surface inflow and bottom outflow are each in geostrophic balance; (3) the observations will be examined to test the premise behind earlier work, that there exists a linear relation between net flow and the sea level difference across the Strait; (4) to evaluate the contribution made by the pressure difference along the axis of the Strait to the flow through the Strait; for the high frequencies: (5) to give a dynamical description of the behavior of the tidal wave as it penetrates the Strait into the Mediterranean (for this purpose sea level data gathered by the IHM along the Spanish coast, at Tarifa and Algeciras, and North-African coast, Ceuta, will also be used); and finally, (6) to evaluate the non-linear interactions between the tides and the low frequency phenomena described above.

Plan: Pressure, temperature and conductivity sensors will be deployed for two consecutive six-month periods in the Strait. These instruments will be located as indicated on the accompanying plan. Four instruments will be located across the sill section. Fluctuations in the sea level across the Strait will be deduced from the pressure difference between the two shallow pressure sensors, while fluctuations in the slope of the interface can be deduced with the observations of pressure at 200 m.



The Strait of Gibraltar and proposed instrument location.

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16. Abstract (Limit: 200 words)

The flow through the Strait of Gibraltar has always held a special fascination for oceanographers. Attempts to understand and measure the strong currents in the Strait stimulated many of the early advances in oceanography (Deacon, 1971). Over the centuries, the focus of scientific investigations has shifted from understanding how the mass budget of the Mediterranean is maintained in the presence of the strong inflow of Atlantic water through the Strait of Gibraltar, to observing the outflow of Mediterranean water over the Gibraltar sill, to measuring the two-layer exchange of Atlantic inflow and Mediterranean outflow through the Strait. In the past few years the focus has again shifted to the study of how the dynamical constraints for flow through a narrow and shallow strait act to control the amount of exchange between the Atlantic and Mediterranean basins. To investigate the dynamics of flow through a strait, a year-long field experiment has been designed to measure the flows through the Strait of Gibraltar, including their time variability over tidal to seasonal time scales, and to assess the importance of friction, mixing, rotation, and nonlinear processes in controlling the exchange through the Strait. This field program, called the Gibraltar Experiment, will be carried out by a group of American, Spanish, Moroccan, Canadian and French scientists during the period from Fall 1985 to Fall 1986.

17. Document Analysis a. Descriptors

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2. Sill Mixing
3. Strait Dynamics

b. Identifiers/Open-Ended Terms

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